The NuSTAR Data Analysis Software Guide

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Table 1-1: Document History

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1 INTRODUCTION

1.1 Scope

This Guide describes the NuSTAR Data Analysis Software (NuSTARDAS), the software package jointly developed by the ASI Science Data Center (ASDC, Italy) and the California Institute of Technology (Caltech, USA) for the processing of scientific data taken with the NuSTAR observatory. This guide describes the processing procedures for the calibration, the screening and the generation of high-level NuSTAR data products (energy spectra, light-curves, sky images) to be used for scientific analysis.

This document does not provide a description of the NuSTAR observatory and of its scientific payload for which the reader is referred to the primary mission description document (Harrison et al., 2013, ApJ, 770, 103). This guide is a living document, following the evolution of the processing algorithms, the calibration information and the data analysis techniques. This version of the guide is written based on the first public version of NuSTARDAS (v. 1.2.0) and associated CALDB version 20130509. It will be regularly updated following the future software changes.

1.2 Software Characteristics

The NuSTARDAS package produces cleaned, calibrated event list files and standard high-level scientific products starting from the FITS formatted telemetry data. The software is designed as a collection of software modules (tasks) each dedicated to a single function. The package includes also a main script, the NuSTAR pipeline (named *'nupipeline'*) allowing users to automatically run in sequence all the tasks for the data processing.

The NuSTAR tasks are written in FTOOLS style and the whole package is fully compatible with the HEASoft software, maintained and distributed by the NASA-HEASARC data center (`http://heasarc.gsfc.nasa.gov`). The NuSTARDAS package is officially integrated in the HEASoft and distributed to the users within its standard public releases. Questions about the NuSTARDAS software package can be addressed to the HEASARC help desk at `http://heasarc.gsfc.nasa.gov/cgi-bin/Feedback` where you should select “NuSTAR” as the mailing list.

Multi-mission FTOOLS from the HEASoft package are also used in several NuSTARDAS modules. The NuSTAR software parameter interface is implemented with the PIL (Parameter Interface Library) library and the I/O with the FITS data files makes use of the FITSIO library.

The NuSTAR software tasks retrieve the calibration files structured in HEASARC's calibration database (CALDB) system. The NuSTARDAS data processing software uses FITS data format following the NASA-OGIP standards as inputs and outputs and makes exclusive use of open source software (C and Perl languages).

1.3 Software Breakdown

The input to the NuSTARDAS package is the NuSTAR FITS formatted telemetry data produced at the NuSTAR Science Operation Center (NuSTAR SOC) in Caltech. The NuSTARDAS data processing is organized in three distinct stages for the calibration, the screening and the extraction of high-level scientific products (see also Figure 1 showing the NuSTARDAS high-level data reduction flow diagram):

1. **Data Calibration**: FITS formatted telemetry processing to produce calibrated event files (*Stage 1*);
2. **Data Screening**: calibrated event files filtering by applying cleaning criteria on specified orbital/instrument parameters and event properties to produce cleaned event files (*Stage 2*);
3. **Products Extraction**: generation of high-level scientific products (light-curves, energy spectra, sky images, Ancillary Response Files, Redistribution Matrix Files) (*Stage 3*).

The processing steps listed above defines the following levels of science data:

- **Level 0**: Raw Telemetry packets;
- **Level 1**: Telemetry formatted in FITS format;
- **Level 1a**: Calibrated Events Files;
- **Level 2**: Cleaned and Calibrated Event Files;
- **Level 3**: High-level Scientific Products (e.g. light-curves, energy spectra, sky images).

The files generated with the NuSTARDAS package (e.g. Level 1a/2 event files, Level 3 energy spectra and light-curves) can be read into widely used high-energy astronomy multi-mission data analysis programs such as XSELECT, XSPEC, XRONOS and XIMAGE.

The NuSTARDAS package is run at the NuSTAR SOC in Caltech where it is used to generate the different levels of NuSTAR scientific archive. The package has also been designed to allow users to reproduce any stage of the data processing which could be necessary, for example, because of improved calibration information, updated software modules or because the user wants to use a non-standard data processing. To this end, the *'nupipeline'* script is the main interface for the users.

Once installed, specific help files for all the NuSTARDAS modules can be viewed by using the command **'fhelp task_name'** (e.g. *'fhelp nupipeline'*).

1.4 Downloading and installing

The NuSTARDAS package is integrated in the NASA-HEASARC HEASoft software and can be downloaded at the following link:

http://heasarc.gsfc.nasa.gov/docs/software/lheasoft/

The installation instructions can be found at the same address. Note that the NuSTAR calibration data provided in the CALDB must be installed[1] in order to process the NuSTAR scientific data.

1.5 Guide Organization

This guide is organized as follows. Chapter 2 describes the NuSTAR data files to provide a basic knowledge of their content, the file naming convention and the archive structure. Chapter 3 gives a description of the processing steps and the software modules involved in the data calibration (Stage 1). Chapter 4 describes the standard screening criteria that are applied to the data and the specific software modules used to produce calibrated and cleaned event files and sky exposure maps (Stage 2). In chapter 5 the third stage of the data reduction, i.e. the generation of high-level data products (e.g. energy spectra,

[1] Users may remotely access the CALDB at HEASARC via the internet, typically by setting the environment variable `$CALDB` as http://heassarc.gsfc.nasa.gov/FTP/caldb Remote access to the CALDB is described in the "CALDB Remote Access" document at http://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/caldb_remote_access.html

light-curves and sky images), is illustrated. Examples of standard data processing command lines are also given at the beginning of Chapters 3, 4 and 5. In Chapter 6 the calibration files used in the data processing are described. Finally, the appendix details the table formats for the NuSTAR science files.

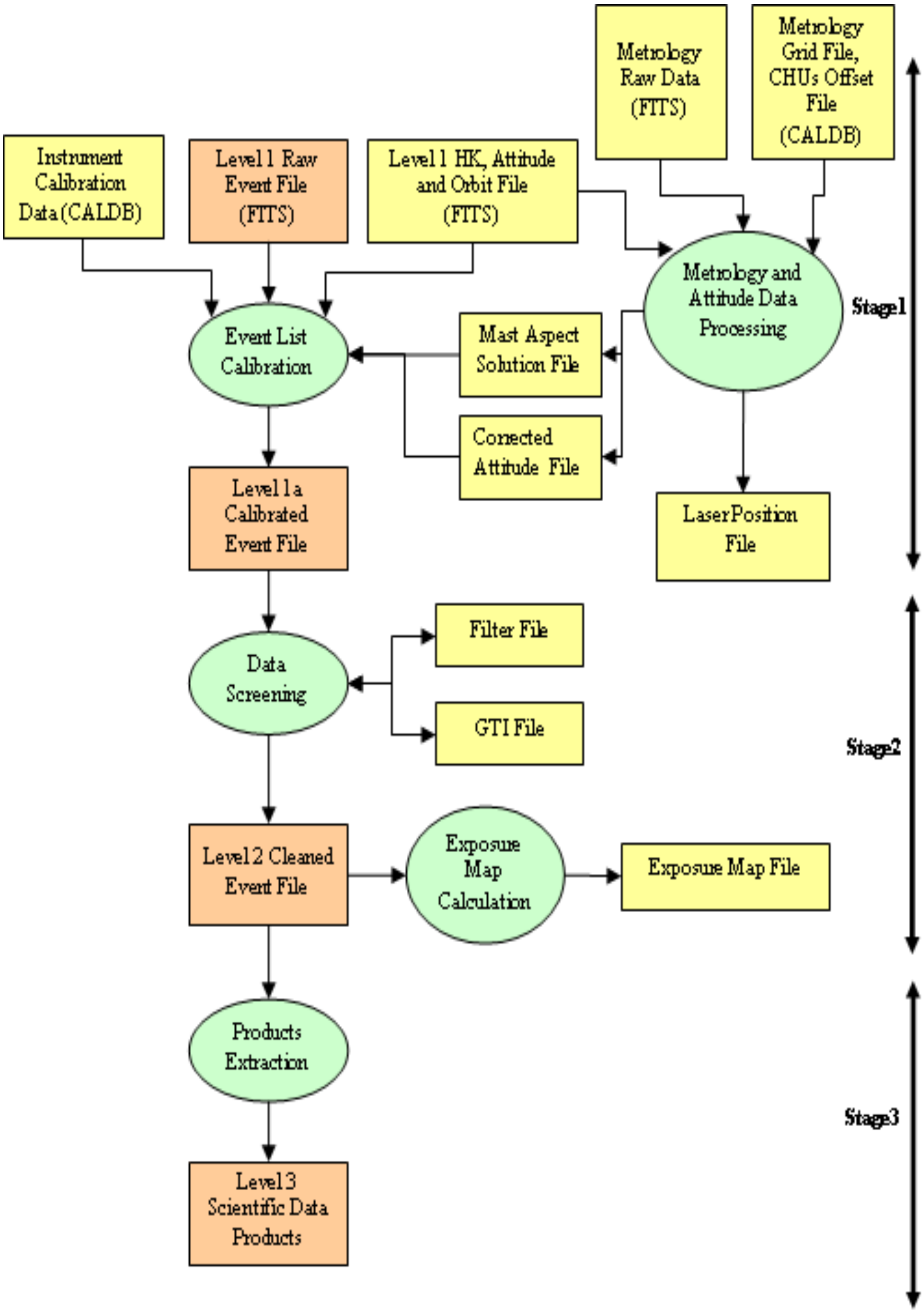

Figure 1: NuSTARDAS data reduction flow diagram

2 NuSTAR DATA FILES

The NuSTARDAS data processing software uses FITS data format following the NASA-OGIP standards as inputs and outputs. In this chapter we provide a basic knowledge of the file naming convention adopted for NuSTAR, their content and how they are located in the NuSTAR archive structure.

2.1 NuSTAR File Naming Convention

The file name format for the NuSTAR science files uses the following convention:

nuObservationID [M][xx]_[ll].ss

where:

- 'nu' is a prefix to indicate the mission name (NuSTAR);
- 'ObservationID' is a 11 digits number to identify the observation (hereafter obsID);
- 'M' is a one character string that identifies the focal Plane Module (A or B);
- 'xx' is a code to identify the observing mode as defined below:
  - 01 (SCIENCE): normal observing scientific mode;
  - 02 (OCCULTATION): Earth in the field of view;
  - 03 (SLEW): data taken during a spacecraft slew;
  - 04 (SAA): South Atlantic Anomaly passages;
  - 05 (CALIBRATION): on-board calibration radioactive source in the field of view;
  - 06 (SCIENCE_SC): attitude reconstruction from the spacecraft bus star trackers;
- 'll' indicates for event files the processing level (*'uf'* for Level 1 and Level 1a files, *'cl'* for Level 2 files). For other data files it describes their content (e.g. *'met'* for raw metrology data, *'mast'* for mast aspect solution file, *'ex'* for exposure maps);
- 'ss' is the file extension and indicates the data type (e.g. *'evt'* for event files, *'img'* for sky images, *'hk'* for housekeeping files, *'lc'* for light-curves, *'pha'* for energy spectra).

The quantities in square brackets can be omitted, for example i) 'M' (A or B) is not used for data files from the metrology laser system and ii) the observing mode code 'xx' is not used for Level 1/1a event files since the data splitting is carried out during the Stage 2 (see Chapter 4).

2.2 Archive Directory Structure

For each observation, the NuSTAR science data files are stored in the archive in a single directory named after the observationID number. Each directory has the following structure:

\observationID

\auxil *\hk* *\event_uf* *\event_cl*

Event files from both focal plane modules, housekeeping, metrology and other types of data (e.g. attitude and orbit files) are contained in different sub-directories according to their content and/or level of processing as detailed below (the obsID 40060001001 is used as an example).

1. The *'auxil'* directory stores the following files:

- `nu40060001001_att.fits` Star tracker attitude file
- `nu40060001001_orb.fits` Orbit file
- `NUSTAR_TLE_ARCHIVE.txt.YYYYDDD` NuSTAR Two-Line Elements file

2. In the *'hk'* directory the following housekeeping FITS files are contained:

- `nu40060001001_ceb.hk` Central Electronics Box (CEB) housekeeping file
- `nu40060001001A_fpm.hk` FPMA instrument housekeeping file
- `nu40060001001B_fpm.hk` FPMB instrument housekeeping file
- `nu40060001001A_dspx.fits` FPMA disabled pixel map file
- `nu40060001001B_dspx.fits` FPMB disabled pixel map file
- `nu40060001001_met.fits` Raw Metrology Data file
- `nu10012006001_chu123.fits` Spacecraft bus star tracker housekeeping file
- `nu10012006001_chu4.fits` Optical bench star tracker housekeeping file
- `nu10012006001_eng.hk` Spacecraft bus attitude quaternion file
- `nu10012006001_obeb.hk` Optical Bench Electronics Box housekeeping file

3. The *'event_uf'* directory stores the Level 1 science event files:

- `nu40060001001A_uf.evt` L1 FPMA event file
- `nu40060001001B_uf.evt` L1 FPMB event file

The above list contains all the input files used for the NuSTARDAS data processing. The output files generated by a full processing (Stages 1, 2 and 3) are stored in the archive *'event_cl'* directory. The output directory can be specified in '*nupipeline*' using the '*outdir*' parameter. A full list of the output files is given below:

Stage1:

```
nu40060001001_psd.fits        Position Sensing Detector file
nu40060001001_psdcorr.fits    Corrected Position Sensing Detector file
nu40060001001_mast.fits       Mast aspect solution file
nu40060001001_att.fits        Corrected star tracker Attitude file
nu40060001001A_fpm.hk         FPMA updated instrument housekeeping file
nu40060001001B_fpm.hk         FPMB updated instrument housekeeping file
nu40060001001A_bp.fits        FPMA Bad Pixel file
nu40060001001B_bp.fits        FPMB Bad Pixel file
nu40060001001A_hp.fits        FPMA Hot Pixel file
nu40060001001B_hp.fits        FPMB Hot Pixel file
nu40060001001A_oa.fits        FPMA Optical Axis file
nu40060001001B_oa.fits        FPMB Optical Axis file
nu40060001001A_det1.fits      FPMA DET1 Reference Pixel file
nu40060001001B_det1.fits      FPMB DET1 Reference Pixel file
nu40060001001A_uf.evt         L1a FPMA calibrated event file
nu40060001001B_uf.evt         L1a FPMB calibrated event file
```

Stage 2:

```
nu40060001001A.mkf            FPMA Filter file
nu40060001001B.mkf            FPMB Filter file
nu40060001001A.attorb         FPMA Prefilter output file
nu40060001001B.attorb         FPMB Prefilter output file
nu40060001001A01_gti.fits     FPMA GTI file for obs. mode 01
nu40060001001B01_gti.fits     FPMB GTI file for obs. mode 01
nu40060001001A01_cl.evt       L2 FPMA event file for obs. mode 01
```

```
nu40060001001B01_cl.evt        L2 FPMB event file for obs. mode 01
nu40060001001A02_gti.fits      FPMA GTI file for obs. mode 02
nu40060001001B02_gti.fits      FPMB GTI file for obs. mode 02
nu40060001001A02_cl.evt        L2 FPMA event file for obs. mode 02
nu40060001001B02_cl.evt        L2 FPMB event file for obs. mode 02
nu40060001001A03_gti.fits      FPMA GTI file for obs. mode 03
nu40060001001B03_gti.fits      FPMB GTI file for obs. mode 03
nu40060001001A03_cl.evt        L2 FPMA event file for obs. mode 03
nu40060001001B03_cl.evt        L2 FPMB event file for obs. mode 03
nu40060001001A04_gti.fits      FPMA GTI file for obs. mode 04
nu40060001001B04_gti.fits      FPMB GTI file for obs. mode 04
nu40060001001A04_cl.evt        L2 FPMA event file for obs. mode 04
nu40060001001B04_cl.evt        L2 FPMB event file for obs. mode 04
nu40060001001A05_gti.fits      FPMA GTI file for obs. mode 05
nu40060001001B05_gti.fits      FPMB GTI file for obs. mode 05
nu40060001001A05_cl.evt        L2 FPMA event file for obs. mode 05
nu40060001001B05_cl.evt        L2 FPMB event file for obs. mode 05
nu40060001001A06_gti.fits      FPMA GTI file for obs. mode 06
nu40060001001B06_gti.fits      FPMB GTI file for obs. mode 06
nu40060001001A06_cl.evt        L2 FPMA event file for obs. mode 06
nu40060001001B06_cl.evt        L2 FPMB event file for obs. mode 06
nu40060001001A01_ex.img        FPMA exposure map for obs. mode 01
nu40060001001B01_ex.img        FPMB exposure map for obs. mode 01
```

Stage 3:

```
nu40060001001A01_sk.img        L3 FPMA image for obs. mode 01
nu40060001001B01_sk.img        L3 FPMB image for obs. mode 01
nu40060001001A01_sr.pha        L3 FPMA source energy spectrum*
nu40060001001B01_sr.pha        L3 FPMB source energy spectrum*
nu40060001001A01_sr.lc         L3 FPMA source light-curve*
nu40060001001B01_sr.lc         L3 FPMB source light-curve*
nu40060001001A01_bk.pha        L3 FPMA background energy spectrum*
nu40060001001B01_bk.pha        L3 FPMB background energy spectrum*
nu40060001001A01_bk.lc         L3 FPMA background light-curve*
nu40060001001B01_bk.lc         L3 FPMB background light-curve*
nu40060001001A01_im.gif/ps     FPMA Sky image plot
nu40060001001A01_ph.gif/ps     FPMA source energy spectrum plot
nu40060001001A01_lc.gif/ps     FPMA source light-curve plot
nu40060001001B01_im.gif/ps     FPMB Sky image plot
nu40060001001B01_ph.gif/ps     FPMB source energy spectrum plot
nu40060001001B01_lc.gif/ps     FPMB source light-curve plot
nu40060001001A01_sr.arf        L3 FPMA source ARF file*
nu40060001001B01_sr.arf        L3 FPMB source ARF file*
nu40060001001A01_sr.rmf        L3 FPMA source RMF file*
nu40060001001B01_sr.rmf        L3 FPMB source RMF file*
nu40060001001A01_src.reg       L3 FPMA source extraction region file
nu40060001001B01_src.reg       L3 FPMB source extraction region file
```

* These files are not delivered to the archive

The content of these files and a description of the processing modules used to generate them will be given in the following chapters.

3 DATA CALIBRATION (STAGE 1)

This chapter describes the Stage 1 of the NuSTAR data reduction during which the calibration steps are applied to the science event files. This stage also includes 1) the processing of the data from the laser metrology system, measuring the observatory mast alignment temporal changes, and 2) the correction of the spacecraft attitude file.

The inputs of the calibration stage are the Level 1 files storing the telemetry data in FITS format. Stage 1 produces in output the Level 1a calibrated event files and the processed metrology and attitude data files.

For the science event files the following data levels are defined:

- Level 1: Event files containing the original telemetry information reformatted into FITS.
- Level 1a: Event files with the same content of the Level 1 with additional calibrated information.

We note that between Level 1 and Level 1a there is no loss of information, i.e. all the telemetry columns are preserved. It is therefore possible to re-run the Stage 1 NuSTAR software modules on the Level 1a event files to apply new calibration updates (data re-processing).

In this Chapter the various NuSTAR software calibration modules are presented in the order used for the standard data processing along with a description of how they can be used. These calibration steps are coded in the first stage of the *'nupipeline'* script and cases of how to run the pipeline are illustrated in the next Section 3.1.

The list of the Stage 1 software modules is the following:

- *numetrology* - Metrology data processing
- *nuattcorr* - Correction of attitude file
- *nuflagbad* - Flagging events for bad pixels
- *nuhotpix* - Searching for hot and flickering pixels
- *nucalcpha* - Energy correction, PHAS and GRADE calculation
- *nucalcpi* - Gain correction and PI column calculation
- *nuflagevt* - Flagging of events according to various cuts criteria
- *nucoord* - Conversion of Raw coordinates into Detector and Sky coordinates
- *nucalcpos* - Conversion of Raw coordinates into Detector coordinates
- *nuskypos* - Calculation of SKY positions of the optical axis, aperture stop center and DET1 reference pixel

3.1 Standard Data Processing with *'nupipeline'* (Stage 1)

The calibration steps described in this chapter are coded in the *'nupipeline'*, the script designed to automatically run in sequence all the tasks of the NuSTAR data processing. The majority of the input parameters of the single software modules can also be set directly running the *'nupipeline'* and appropriate default values have been set for most of them.

The *'nupipeline'* script assumes that the data files have been downloaded from the archive and it searches in the obsID directory structure for the input files. The directory path of the obsID and the stem of the input files must be provided in input through the parameters *'indir'* and *'steminputs'*, respectively.

The *'exitstage'* input parameters of *'nupipeline'* allows the users to terminate the data reduction at different processing stages (described in Chapter 1). The default value is *'exitstage*=2', i.e. the data are calibrated *and* screened (see next chapter). Below we provide an example of how to run *'nupipeline'* to execute the complete Stage 1 for a standard NuSTAR data processing:

```
> nupipeline indir=/archive/40060001001/ steminputs=nu40060001001
  outdir=./event_cl exitstage=1
```

By default, the *'nupipeline'* processes data files for both Focal Plane Modules (FPMA and FPMB). By setting the input parameter *'instrument'* to *'FPMA'* or *'FPMB'* the users can choose to process only the event files of a single Focal Plane Module, as illustrated below for FPMB:

```
> nupipeline indir=/archive/40060001001/ steminputs=nu40060001001
  outdir=./event_cl exitstage=1 instrument=FPMB
```

3.2 Metrology Data Processing (*'numetrology'*)

The NuSTARDAS software module *'numetrology'* processes the data from the laser metrology system, the device on-board NuSTAR tracking temporal changes of the alignment of the mast connecting the detectors focal plane and the optical bench mirror system.

The task requires in input the following files (parameter names are given in parenthesis):

- Raw Metrology File (*metrologyfile*)
- CALDB Metrology grid File (*metgridfile*)
- CALDB Spacecraft Alignment File (*alignfile*)

The files generated in output by the task are:

- Position Sensing Detector File (*outpsdfile*)
- Corrected Position Sensing Detector File (*outpsdfilecor*)
- Mast Aspect Solution File (*mastaspectfile*)

The task first calculates the X and Y positions as a function of time of the laser spots on the two Position Sensing Detectors ('PSD0' and 'PSD1') located on the detectors focal plane bench. The X/Y coordinates are written in the output file specified through the input parameter *'outpsdfile'*.

Next, the X/Y coordinates are corrected for the distortions introduced by the response of the two laser detectors. To this end, the information stored in the CALDB Metrology Grid file (read in input via the parameter *'metgridfile'*) is used and the results are stored in the output file *'outpsdfilecor'*. During this step, a specific column, named 'METGRID_FLAG', is added to the *'outpsdfilecor'* file to flag time intervals during which the laser spots fall outside the X and/or Y ranges covered by the Metrology Grid File.

In the third step, the lasers positions are used to calculate the Mast Aspect Solution File storing, as a function of time, the roto-translations tracking the spacecraft mast movements. The roto-translations terms are written in the columns 'T_FBOB' and 'Q_FBOB' of the output file *'mastaspectfile'*.

The task processes the raw metrology data (steps 1 and 2 described above) if the input parameter *'metflag'* is set to *'yes'* (default value). By setting *'metflag=no'* only the step 3 is executed by the task and the corrected Position Sensing Detector File must be provided in input by the user through the parameter *'inpsdfilecor'*.

Usage Example:

1. Process the raw metrology data file 'nu40060001001_met.fits' using the calibration information stored in the CALDB. The mast aspect solution file is written in the output file 'nu40060001001_mast.fits'. The X/Y coordinates of the PSD detectors, before and after the correction for the distortions, are stored in the output files 'nu40060001001_psd.fits' and 'nu40060001001_psdcorr.fits', respectively.

```
> numetrology metrologyfile=nu40060001001_met.fits
```

3.3 Attitude File Correction (*'nuattcorr'*)

The NuSTARDAS software module *'nuattcorr'* corrects the attitude file for the offset between the Spacecraft Bus (SC) and the Camera Head Unit #4 (CHU4) coordinate system. The task applies the correction only to the data derived from the spacecraft bus star trackers (CHU123), i.e. to the attitude file rows with the column 'SOURCE=2'. The offset is given by a quaternion read from the CALDB file *'chuoffsetfile'*.

The task requires in input the following files:

- Attitude File (*attfile*)
- CALDB CHUs Quaternion Offset File (*chuoffsetfile*)

The files generated in output by the task are:

- Corrected Attitude File (*outattfile*)

Usage Example:

1. Apply the offset quaternion to the input attitude file 'nu40060001001_att.fits'. The corrected attitude file is written in the output file 'nu40060001001_att_corr.fits'.

```
> nuattcorr attfile=nu40060001001_att.fits
  outattfile=nu40060001001_att_corr.fits
```

3.4 Bad Pixels Flagging (*'nuflagbad'*)

The NuSTARDAS software module *'nuflagbad'* flags events occurring in known bad pixels of the NuSTAR detectors.

The task requires in input the following files:

- Level 1/1a Event File (*infile*)
- On-board disabled pixel file (*dispixfile*)
- CALDB on-ground bad pixel file (*bpfile*)
- User bad pixel file (user*bpfile*)

The files generated in output by the task are:

- Calibrated Level 1a Event File (*outfile*)
- Bad Pixels File (*outbpfile*)

Three different input files that identify bad pixels can be used by the task for event flagging:

1. On-ground CALDB Bad Pixel Calibration File including the most up to date information about known stable bad pixels;

2. Disabled Pixel File storing the list of pixels disabled by the on-board processing for the current observation;
3. User supplied Bad Pixel File including the list of additional bad pixels provided by the user.

The on-ground CALDB Bad Pixel File and the User Bad Pixel File contain for each bad pixel a column 'TIME' including the start epoch at which the pixel has to be considered bad. The Disabled Pixel File, including the list of pixels disabled by the on-board software for the current observation, stores for each disabled pixel the corresponding time interval in the columns 'TIME' and 'TIME_STOP'.

All events are flagged using the information obtained from the three input bad pixel files and the user can choose which bad pixel file to use. Events are marked using the *'nuflagbad'* module by adding/updating the 'STATUS' column of the input Level 1/1a event file. The format of this column is a 16-bit binary number and the value of the 'STATUS' column specifies the quality of the flagging (i.e. if the event falls on a stable bad pixel from the on-ground CALDB File or on an on-board disabled pixel).

The task also flags events if any of the 8 neighborhood pixels falls on a bad pixel or outside the detector boundaries (i.e. the event is located on a detector edge). The position of these neighbor pixels is stored in a new column 'BADPOS' added/updated by the task. The format of this column is an 8-bit binary number.

The list of flags in the 'STATUS' column used by the task is the following:

- b0000000000000001 Event falls in a bad pixel from on-ground CALDB Bad Pixel File
- b0000000000000010 Event falls in a bad pixel from on-board disabled pixel
- b0000000000000100 Event falls in a bad pixel from user bad pixel file
- b0000000000001000 Event has a neighbor bad from bad/disabled/user pixel list
- b0000000000010000 Event falls in a detector edge pixel

In addition to the event flagging, the task also stores the list of bad pixels in four distinct 'BADPIX' extensions, one for each of the four detectors, of the input event file. Optionally, if requested by the user through the parameter *'outbpfile'*, the bad pixels list is also written in a separate output file. The 'BADPIX' extensions contain the positional and temporal information and a 16-bit binary number column, named 'BADFLAG', indicating the class of the bad pixel with the following meaning:

- b0000000000000001 Bad pixel from on-ground CALDB Bad Pixel File
- b0000000000000010 Disabled pixel from on-board software
- b0000000000000100 Bad pixel in the file provided by the user

Usage Examples:

1. Flag the events of the input event file 'nu40060001001A_uf.evt' considering the bad pixels listed in the on-ground CALDB Bad Pixel File and in the Disabled Pixel File named 'nu40060001001A_dspx.fits'. The list of bad pixels is stored in the 'BADPIX' extensions of the output event file ('nu40060001001A_out.evt') and in the output bad pixel fits file named 'nu40060001001A_bp.fits'.

```
> nuflagbad infile=nu40060001001A_uf.evt outfile=nu40060001001A_out.evt
  dispixfile=nu40060001001A_dspx.fits outbpfile=nu40060001001A_bp.fits
```

2. Flag the events of the input event file 'nu40060001001A_uf.evt' considering the bad pixels listed in the on-ground CALDB Bad Pixel File, in the Disabled Pixel File named 'nu40060001001A_dspx.fits' and in a user provided file named 'userbadpix.fits'. The list of bad pixels is stored in the 'BADPIX' extensions of the output event file ('nu40060001001A_out.evt').

```
> nuflagbad infile=nu40060001001A_uf.evt outfile=nu40060001001A_out.evt
  dispixfile=nu40060001001A_dspx.fits userbpfile=userbadpix.fits
  outbpfile=NONE
```

3.5 Hot Pixels Searching and Flagging (*'nuhotpix'*)

The NuSTARDAS software module *'nuhotpix'* searches and flags anomalous (hot and flickering) pixels. These are detector pixels that may show unstable states of noise signature and if this signal is much greater then the background level they appear as isolated pixel signals resembling X-ray events.

The task requires in input the following files:

- Level 1/1a Event File (*infile*)

The files generated in output by the task are:

- Calibrated Level 1a Event File (*outfile*)
- Hot Pixels File (*outhpfile*)

The hot/flickering pixels search is achieved by applying statistical tests to a set of counts images generated from the input event file. Each counts image is accumulated during a time interval with a duration defined by the input parameter *'binsize'.*

For each image, hot/flickering pixels are identified comparing the counts in each pixel to the mean background counts. First, for each pixel, the probability for its counts to be a Poisson fluctuation of the mean background of the detector is computed. The parameter *'impfac'* allows the user to rescale the background level. If the pixel probability is lower than a Poisson probability threshold (set by the user through the parameter *'logpos'*), the pixel is considered a hot/flickering pixel candidate. To confirm the hot/flickering pixel candidates, their counts are compared to the mean counts of the surrounding pixels in a square cell with size of the order of the Point Spread Function (parameter *'cellsize'*) to discriminate a hot/flickering pixel from a pixel of a celestial X-ray source in the field of view.

As a second step, by setting the parameter *'cleanflick'* to "yes" (default), hot/flickering pixels are searched using a background estimated locally in its surrounding pixels contained in a cell with size defined by *'cellsize'*. If the local background is zero, the pixel is flagged as hot/flickering if the number of its counts is larger than a threshold value set by the parameter *'bthresh'*. In this second step, setting the parameter ‘iterate’ to ‘yes’ enables iterating the search for hot/flickering pixels.

As in the case of the *'nuflagbad'* task, the *'nuhotpix'* module updates the 'STATUS' column of the event file. The task also flags events if any of the 8 neighborhood pixels falls on a hot/flickering pixel. The position of these neighbor pixels is stored in a new column, named 'HOTPOS', added by the task. The format of this column is an 8-bit binary number.

The values of the 'STATUS' column used by 'nuhotpix' is the following:

- b0000000000100000 Event falls in a hot/flickering pixel
- b0000000001000000 Event has a neighbor hot/flickering pixel

In addition to the event flagging, the task also stores the list of hot/flickering pixels in four distinct 'BADPIX' extensions, one for each of the four detectors, of the input event file. Optionally, if requested by the user through the parameter *'outhpfile'*, the bad pixels list is also written in a separate output file. The 'BADPIX' extensions contain the positional and temporal information and a 16-bit binary number column, named 'BADFLAG', indicating the class of the bad pixel. The start and end time values of the time interval where the pixel is hot/flickering is also stored in the two columns 'TIME' and 'TIME_STOP'. The 16-bit binary number column 'BADFLAG' (see 'nuflagbad' help file) is updated by 'nuhotpix' as follows:

- b0000000000100000 Event falls in a hot/flickering pixel

Usage Examples:

1. Search and flag hot/flickering pixels in the NuSTAR event file named nu40060001001A_uf.evt. The list of hot/flickering pixels is stored in the 'BADPIX' extensions of the output event file and in the output hot pixel fits file named 'nu40060001001A_outhp.fits'.

```
> nuhotpix infile=nu40060001001A_uf.evt outfile=nu40060001001A_out.evt
```

3.6 Energy Corrections, Event Reconstruction and GRADE Assignment (*'nucalcpha'*)

The NuSTARDAS software module *'nucalcpha'* processes the NuSTAR event files to correct photon energies, reconstruct events and assign a grade to each event.

The task requires in input the following files:

- Level 1/1a Event File (*infile*)
- CALDB Capacitor Offset File (*offsetfile*)
- CALDB Grade File (*gradefile*)
- CALDB PHA Parameter File *(phaparfile*)

The files generated in output by the task are:

- Calibrated Level 1a Event File (*outfile*)

As a first step, various corrections to the energy of the events are applied. The *'nucalcpha'* task reads the 'PREPHAS' and 'POSTPHAS' columns of the input event files storing, for each event, the nine charge values (of the 3x3 square pixel array) taken before and after the on-board trigger, respectively. The pre-trigger values are first subtracted from the post-trigger ones and then the "capacitor offset", the "time of rise" and the "common mode" corrections are applied to the energies.

The corrected energies are written in the 'PHAS' column of the output event file. Moreover, the task adds/updates the 'SWTRIG' column of the output event file. The algorithm used is summarized below.

For each event (3x3 pixels array) the task applies the following processing steps:

1. Computation of RAWPHAS (9 dimensional vector):

   RAWPHAS[9] = POSTPHAS[9] - PREPHAS[9]

2. Offset correction, i.e. computation of 'OFFPHAS' (9 dimensional vector):

   OFFPHAS[9] = RAWPHAS[9] - OFFSET[9]

where the 9 values of OFFSET[9] are read from the input CAP_OFFSET file and are dependent on:

- the coordinates (RAWX, RAWY) of the pixels (3X3 array)
- the capacitor number (S_CAP column) of the event the detector (DET_ID column)

3. Time of rise correction, i.e. computation of 'TRPHAS' (9 dimensional vector):

   TRPHAS[9] = OFFPHAS[9] * (1+(NUMRISE/DENRISE)*TIMERISE[9])

where NUMRISE, DENRISE are read from the input event file. The 9 values of TIMERISE[9] are read by default from the input PHAPAR file and are dependent on:

- the coordinates (RAWX, RAWY) of the pixels (3X3 array)
- the detector (DET_ID column)

If the parameter 'phaparfile' is set to 'NONE', the 9 values are provided in input to the task through the specific parameter 'timerise' (default=0.0016).

4. Common mode correction, i.e. computation of 'PHAS' (9 dimensional vector):

    4a) exclusion of the M pixels located out of the detector or falling on bad/hot pixels

    4b) selection of the N pixels ("E+") with TRPHAS >= 'EVTTHR[9]' (not including the M pixels defined in point 4a)

    4c) selection of the 9-N-M pixels ("E-") with TRPHAS < 'EVTTHR[9]'

    The 9 values of EVTTHR[9] are read by default from the input PHAPAR file and are dependent on:

    - the coordinates (RAWX, RAWY) of the pixels (3X3 array)
    - the detector (DET_ID column)

    If the parameter 'phaparfile' is set to 'NONE', the 9 values are provided in input to the task through the specific parameter 'evtthr' (default=55).

    4d) calculation of the mean of the pixels with TRPHAS < 'EVTTHR[9]':

    < E- >=(&sum E-)/(9-N-M)

    4e) computation of PHAS (9 dim. vector) for the N pixels "E+":

    PHAS[9] = TRPHAS[9] - < E->

    4f) computation of PHAS (9 dim. vector) for the 9-N-M pixels "E-":

    PHAS[9] = TRPHAS[9]

    4g) setting to zero PHAS values for the M pixels out of detector:

    PHAS[9] = 0

5. computation of 'SWTRIG' column (9 dimensional vector):

    SWTRIG[9] = 1 for pixels with TRPHAS >= 'EVTTHR[9]'

    SWTRIG[9] = 0 for pixels with TRPHAS < 'EVTTHR[9]'

In the second step, the task reconstructs the event charge splitting topology and assigns to them a grade following a charge pattern definition stored in the input CALDB file *'gradefile'* (see Figure 2). The values of the event grades are written in the 'GRADE' column of the output event file.

Usage Examples:

1. Calculate PHAS and GRADE values for the event file 'nu40060001001A_uf.evt'. The values of the event software threshold, the time of rise correction coefficients, the capacitor offset values and the GRADE classification are read from the specific CALDB files. The results are written in the output event file 'nu40060001001A_out.evt'.

```
> nucalcpha infile=nu40060001001A_uf.evt outfile=nu40060001001A_out.evt
```

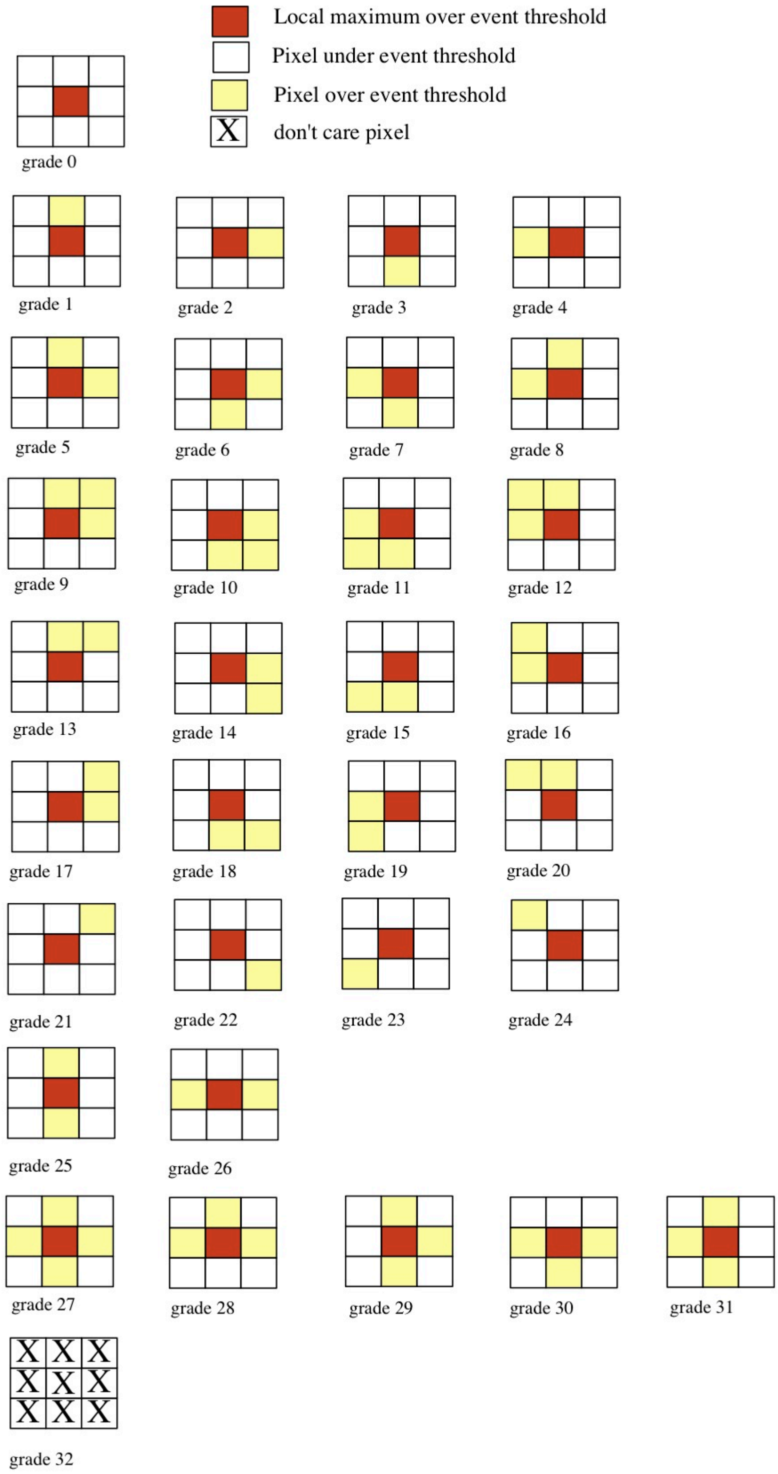

Figure 2: Definition of the NuSTAR event grades

3.7 Gain Correction (*'nucalcpi'*)

The NuSTARDAS software module *'nucalcpi'* processes the NuSTAR event files to convert the charge associated to each event from electronic units ("Pulse Height Amplitude", PHAS) into physical energy units ("Pulse Invariant", PI) by applying gain corrections.

The task requires in input the following files:

- Level 1/1a Event File (*infile*)
- Instrument Housekeeping File (*hkfile*)
- CALDB Gain File (*gainfile*)
- CALDB Charge Loss Correction File *(clcfile*)
- CALDB Charge Loss Correction Filter File *(clcfilterfile*)

The files generated in output by the task are:

- Calibrated Level 1a Event File (*outfile*)

The *'nucalcpi'* task applies a conversion between signal charge and photon energy, which is pixel, grade and temperature dependent. In addition, a temporal evolution of the gain is also included. Specifically, the task reads, for each event, the 'PHAS' column of the input event file and the temperature associated to each event from the input Housekeeping file. Moreover, its position on the detector ('RAWX', 'RAWY' columns) and its grade ('GRADE' column) are read.

Next, by using the gain values stored in the CALDB gain file (parameter *'gainfile'*), the task calculates the energy in physical units and stores the values in a new column (named 'PI') of the output event file. Also, specific charge-loss corrections for multiple pixels events are applied using information from the two input CALDB files *'clcfile'* and *'clcfilterfile'*.

The task also computes the PI values for the 3x3 array pixels below the software threshold and stores the result in the 'SURRPI 'column.

The gain coefficient values have been evaluated from ground calibration data at three fixed temperatures of the detector and may be periodically updated using the results of the flight calibration data analysis. The charge loss correction is applied to events with grades 1-8 using the information stored in the input CALDB Charge Loss Correction and Charge Loss Correction Filter files.

The PI calculation is the result of an interpolation on temperature and on time. First, for each event the two rows valid for the epochs closest to the time of the event are chosen. Then for each row, given the temperature associate to the event, the task performs a temperature interpolation of the gain coefficients between the two nearest temperatures, thus obtaining two sets of coefficients for two contiguous times. Finally, a second interpolation with respect to time between these two sets of coefficients is performed.

The temperature of each event is read from the input Housekeeping file (input parameter *'hkfile'*). Optionally, by setting *'hkfile'* to 'NONE', the temperature associated to all the events is read from the input parameter *'temperature'*.

The unit of the 'PI' and 'SURRPI' columns is set to 40 eV per channel.

Usage Examples:

1. Calculate PI values for the input event file 'nu40060001001A_uf.evt'. The detector temperature associated to each event is read from the input file 'nu40060001001A.hk'. The results are written in the output event file 'nu40060001001A_out.evt'.

```
> nucalcpi infile=nu40060001001A_uf.evt outfile=nu40060001001A_out.evt
  hkfile=nu40060001001A_fpm.hk
```

3.8 Events Flagging (*'nuflagevt'*)

The NuSTARDAS software module *'nuflagevt'* flags the events of NuSTAR event files according to various conditions.

The task requires in input the following files:

- Level 1/1a Event File (*infile*)
- CALDB Depth Cut File (*depthcutfile*)
- CALDB Event Cut File (*eventcutfile*)

The files generated in output by the task are:

- Calibrated Level 1a Event File (*outfile*)

The *'nuflagevt'* task first flags the events on the basis of their depth of interaction in the detectors, accounting for the total absorption probability in CZT along the direction of the original photon. The aim is to flag the internal detector background events thus improving the S/N.

The depth cut profiles are read from the input CALDB file *'depthcutfile'* which stores, for each pixel of the detectors, three energy depth cut channels 'E1', 'E2' and 'E3' as a function of the event energy. For each event, *'nuflagevt'* selects the CALDB 'E1', 'E2' and 'E3' values corresponding to its position on the detector and energy ('RAWX', 'RAWY' and 'PI' columns on the input event file) and flags it according to the following criteria:

- `SURRPI ≤ E1       (if E2,E3 > 0)`
- `E2 < SURRPI ≤ E1 (if E2,E3 < 0)`
- `SURRPI ≤ E3       (if E2,E3 < 0)`

where 'SURRPI' is a column read from the input event file and stores the sum of the energies of the untriggered surrounding pixels, i.e. the pixels in the 3x3 array which are below the software threshold.

Next, the task flags events according to the values of the 'PRIOR', 'RESET', 'PREPHAS[5]', and 'PI' columns of the input event file. Specifically, "baseline", "prior/reset", "prior", "reset" and "energy" cuts are applied using specific conditions on the values of these columns as detailed below:

1. "Baseline cut":
   - `(BASELINE < BASELINE1 and PI < PI_BASELINE) or (BASELINE > BASELINE2)`
2. "Prior/reset cut" (FPMA only):
   - `(PRIOR2 < PRIOR < PRIOR3 and PI < PI_PRIOR) or`
   - `(RESET2 < RESET < RESET3 and PI1_RESET < PI < PI2_RESET)`
3. "Prior cut":
   - `PRIOR < PRIOR1`
4. "Reset cut":
   - `RESET < RESET1`
5. "Energy cut":
   - `PI < 0 or PI > 4095`

where the threshold values *BASELINE1, PI_BASELINE, BASELINE2, PRIOR1, PRIOR2, PRIOR3, PI_PRIOR, RESET1, RESET2, RESET3, PI1_RESET, PI2_RESET* are read from the input CALDB file 'evtcutfile'.

As in the case of the *'nuflagbad'* module, the task updates the 'STATUS' column of the event file. The values of the 'STATUS' column used by *'nuflagevt'* are the following:

- b0000000010000000 Event fails depth cut
- b0000000100000000 Event fails baseline cut
- b0000001000000000 Event fails prior/reset cut
- b0000010000000000 Event fails prior cut
- b0000100000000000 Event fails reset cut
- b0001000000000000 Event with PI out of range

Usage Examples:

1. Flag events in the NuSTAR event file named nu40060001001A_uf.evt. The 'STATUS' column of the output event file 'nu40060001001A_out.evt' is updated accordingly.

```
> nuflagevt infile=nu40060001001A_uf.evt outfile=nu40060001001A_out.evt
```

3.9 Coordinates Transformation (*'nucoord'*)

The NuSTARDAS software module *'nucoord'* converts the coordinates of each event from the telemetry raw sub-detector (hybrid) values into celestial sky coordinates using information from the Mast Aspect Solution File and the Spacecraft Attitude File.

The following four coordinates systems are defined (event files columns names are indicated in parenthesis):

- (RAWX, RAWY): telemetry sub-detector (hybrid) coordinates (pixel size = 12.3'')
- (DET1X, DET1Y): Focal Plane Bench Frame (FB) detector coordinates (pixel size = 2.46'')
- (DET2X, DET2Y): Optics Bench Frame (OB) detector coordinates (pixel size = 2.46'')
- (X, Y): Celestial Sky Coordinates (pixel size = 2.46'')

The *'nucoord'* task also calculates, as a function of time, the sky positions of the telescope optical axis, of the aperture stop center and of a reference pixel of the detector.

The task requires in input the following files:

- Level 1/1a Event File (*infile*)
- Mast Aspect Solution File (*mastaspectfile*)
- Spacecraft Attitude File (*attfile*)
- CALDB Pixel Location File (*pixposfile*)
- CALDB Spacecraft Alignment File (*alignfile*)
- CALDB Telescope Definition File (*teldef*)

The files generated in output by the task are:

- Calibrated Level 1a Event File (*outfile*)
- Optical Axis File (*optaxisfile*)
- DET1 Reference Pixel File (*det1reffile*)

The *'nucoord'* module is a script that runs in sequence the software modules *'nucalcpos'*, *'coordinator'* and *'nuskypos'*. These modules are discussed in the following sub-sections.

3.9.1 Detector Coordinates Calculation (*'nucalcpos'*)

The first module run by '*nucoord*' is the *'nucalcpos'* task to calculate the detector coordinates in the detectors Focal Plane Bench Frame ('DET1') and in the Optics Bench Frame ('DET2') starting from the telemetry sub-detector coordinates ('RAW' system).

The task requires in input the following files:

- Level 1/1a Event File (*infile*)
- Mast Aspect Solution File (*mastaspectfile*)
- CALDB Pixel Location File (*pixposfile*)
- CALDB Spacecraft Alignment File (*alignfile*)

The files generated in output by the task are:

- Calibrated Level 1a Event File (*outfile*)

The *'nucalcpos'* task reads the ‘RAWX’ and ‘RAWY’ columns of the input event file storing the original telemetry coordinates of the events for each of the four focal plane module sub-detectors (*'DET0'*, *'DET1'*, *'DET2'* and *'DET3'*). For each sub-detector, the range of the 'RAWX' and 'RAWY' columns is 0-31.

As a first step, the task transforms the RAW coordinates of the four sub-detectors in a new common coordinate system referred to the detectors Focal Plane Bench Frame (FB). This first step includes a change of the pixel size (by a factor of 1/5) and a correction of the detector pixels positions using the information from the input CALDB pixel location file (parameter *'pixposfile'*).

The new coordinates values are saved in two new columns (‘DET1X’ and ‘DET1Y’) of the output event file. The DET1 pixel size is 12.3/5=2.46 arc seconds and the column range is 1-360. The coordinates transformation between the 'RAW' and the 'DET1' system is illustrated in Figure 3.

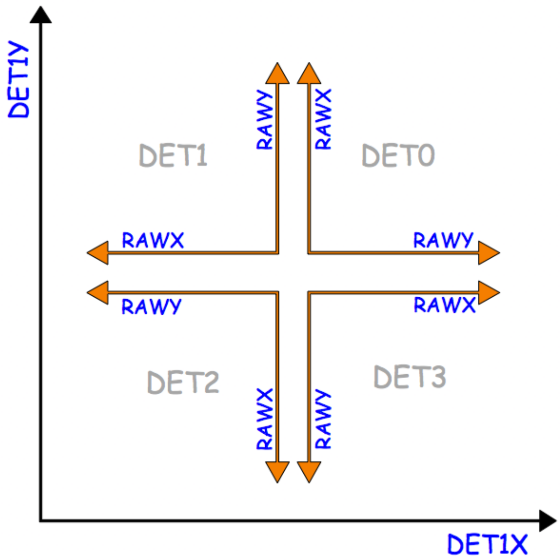

Figure 3: Relationship between the raw telemetry coordinates of the four sub-detectors (coordinates 'RAWX', 'RAWY') and the Focal Plane Bench Frame (coordinates 'DET1X', 'DET1Y').

Next, the task uses the time dependent roto-translations stored in the Mast Aspect Solution file to calculate the detector coordinates in the Optics Bench Frame (OB). These coordinates are written in two new columns (‘DET2X’ and ‘DET2Y’) of the output event file.

This transformation enables the correction of coordinates for the movement of the deployed mast connecting the detectors Focal Plane Bench to the Optics Bench. The coordinates transformation between the 'DET1' and the 'DET2' systems is illustrated in Figure 4.

The DET2 pixel size is the same as the DET1 system size (2.46 arc seconds) while the column range is 1-600. Additional details on the algorithm can be found in the help file of the task.

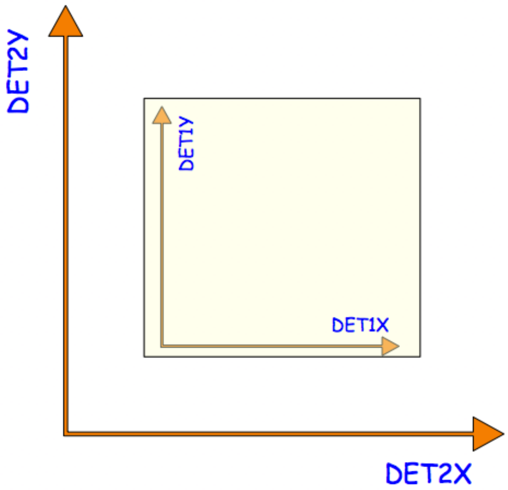

Figure 4: Relationship between the detector coordinates in the Focal Plane Bench frame (columns 'DET1X','DET1Y') and in the Optics Bench frame (columns 'DET2X', 'DET2Y').

3.9.2 Sky Coordinates Calculation (*'coordinator'*)

The second module run by '*nucoord*' is the *'coordinator'* FTOOL. This is a multi-mission tool distributed by the HEASARC as part of the HEASoft package. For NuSTAR it is used to convert the 'DET2' coordinates in 'SKY' celestial coordinates taking into account the spacecraft attitude information.

The task requires in input the following files:

- Level 1/1a Event File (*infile*)
- Spacecraft Attitude File (*attfile*)
- CALDB Telescope Definition File (*teldef*)

The files generated in output by the task are:

- Calibrated Level 1a Event File (*outfile*)

The SKY celestial coordinates are stored in two new columns (‘X’ and ‘Y’) of the output event file. The 'X' and 'Y' column range is 1-1000.

3.9.3 Optical Axis, Aperture Stop Center and Detector Reference Pixel Sky Positions (*'nuskypos'*)

The third module run by 'nucoord' is the NuSTARDAS task *'nuskypos'* that calculates, as a function of time, the sky positions of the telescope optical axis, of the aperture stop center and of a reference pixel of the detector in the DET1 coordinate system.

The task requires in input the following files:

- Mast Aspect Solution File (*mastaspectfile*)
- Spacecraft Attitude File (*attfile*)
- CALDB Spacecraft Alignment File (*alignfile*)
- CALDB Telescope Definition File (*teldef*)

The files generated in output by the task are:

- Optical Axis File (*optaxisfile*)
- DET1 Reference Pixel File (*det1reffile*)

As a first step, the *'nuskypos'* task reads the position of the optical axis in the DET2 frame from the input CALDB spacecraft align file (parameter *'alignfile'*) and transforms it in the SKY frame. This allows the motion of the optical axis to be tracked in the SKY coordinate system and it is used to calculate the off-axis angle of a given celestial source by the *'numkarf'* task during the Stage 3. The SKY position of the optical axis as a function of time is stored in the output file *'optaxisfile'*.

The 'nuskypos' module also calculates the DET2 and SKY coordinates of the center of the aperture stop. The location of the aperture stop center in the DET1 frame is stored in the CALDB *'alignfile'*. The task first reads this position and converts the Focal Plane Bench Frame (DET1) coordinates into the Optics Bench Frame (DET2) detector coordinates using the mast aspect solution file (parameter *'mastaspectfile'*). Afterward, the DET2 coordinates are transformed in SKY coordinates using the input spacecraft attitude and teldef files. The DET2 and SKY positions of the aperture stop center are stored in the output file *'optaxisfile'*.

Finally, *'nuskypos'* calculates, as a function of time, the SKY coordinates of a reference pixel in the DET1 frame using information from the mast aspect solution file and the spacecraft attitude file. This information is used by the *'nuexpomap'* task to generate the exposure maps. The SKY position of the detector reference point as a function of time is stored in the output file *'det1reffile'*. Additional details about the algorithm can be found in the help file of the task.

Usage Examples:

1. Convert the RAW coordinates of the input event file 'nu40060001001A_uf.evt' to DET1 and DET2 coordinates using the pixel location file stored in the CALDB. The DET1X/DET1Y and DET2X/DET2Y coordinates are written in the output file 'nu40060001001A_out.evt'.

```
> nucalcpos infile=nu40060001001A_uf.evt outfile=nu40060001001A_out.evt
  mastaspectfile=nu40060001001_mast.fits
```

2. Calculate the SKY positions of the optical axis file and of the (350,350) DET1 reference pixel and store them in the output files 'nu40060001001A_oa.fits', 'nu40060001001A_det1.fits', respectively.

```
> nuskypos mastaspectfile=nu40060001001_mast.fits instrument=FPMA
  attfile=nu40060001001_att.fits pntra=258.3014 pntdec=-23.7678
  alignfile=nuCalign20100101v007.fits teldef=nuA20100101v002.teldef
```

```
optaxisfile=nu40060001001A_oa.fits det1reffile=nu40060001001A_det1.fits
```

3. Convert the RAW coordinates of the input event file 'nu40060001001A_uf.evt' to DET1, DET2 and SKY coordinates using the pixel location file stored in the CALDB. The DET1X/DET1Y, DET2X/DET2Y and X/Y coordinates are written in the output file 'nu40060001001A_out.evt'. The optical axis file and the DET1 reference file are also generated.

```
> nucoord infile=nu40060001001A_uf.evt outfile=nu40060001001A_out.evt
  mastaspectfile=nu40060001001_mast.fits attfile=nu40060001001_att.fits
  pntra=258.3014 pntdec=-23.7678 optaxisfile=nu40060001001A_oa.fits
  det1reffile=nu40060001001A_det1.fits
```

4 EVENTS SCREENING AND EXPOSURE MAPS GENERATION (STAGE 2)

This chapter describes the Stage 2 of the NuSTAR data reduction devoted to the screening of event files by applying cleaning criteria on specified attitude/orbital/instrument parameters and event properties. Stage 2 also includes the generation of sky exposure maps.

The inputs of the screening stage are the Level 1a calibrated event files. Stage 2 produces in output the Level 2 calibrated and cleaned event files to be used for scientific analysis. In the following the Stage 2 NuSTAR software modules are presented in the same order used for the standard data processing along with software usage examples. These processing steps are coded in the second stage of the *'nupipeline'* script and cases of how to run the pipeline are illustrated in the next section.

The list of the Stage 2 software modules is the following:

- *nucalcsaa* – Calculation of the SAA passages
- *nufilter* - Filter file generation.
- *nuscreen* - Good Time Intervals generation and event file screening.
- *nulivetime* - Event files dead time correction.
- *nuexpomap* - Sky exposure maps generation.
- *nuskytodet* – Calculation of the DET1 and DET2 coordinates from SKY coordinates.

4.1 Standard Data Processing with *'nupipeline'* (Stages 1 and 2)

The data reduction steps described in this chapter are coded in the *'nupipeline'* script. The majority of the input parameters of the single software modules can also be set directly running the *'nupipeline'* and appropriate default values have been set for most of them.

By setting the input parameter *'exitstage=2'* (default value), the *'nupipeline'* script allows calibration (stage 1) and screening (stage 2) of the data using a single command line. Both data from the FPMA and the FPMB modules are processed by default. The standard command to be used is:

```
> nupipeline indir=/archive/40060001001/ steminputs=nu40060001001
  outdir=./event_cl
```

Note that in this command line it is not necessary to specify *'exitstage=2'* since *'2'* is the default value of this parameter. All the 'nupipeline' output files are generated in a directory named *"event_cl"*.

To generate also the sky exposure maps the input parameter *'createexpomap'* must be set to *'yes'* (default value is *'no'*) as illustrated in the following command line:

```
> nupipeline indir=/archive/40060001001/ steminputs=nu40060001001
  outdir=./event_cl createexpomap=yes
```

4.2 Rationale

The calibrated Level 1a event files can include "bad" events and/or *"bad"* time intervals that need to be excluded before the files can be used for the scientific data analysis. This chapter lists the criteria and the methods that are used to screen the data.

The NuSTAR Calibration Team has defined the standard screening criteria used to produce the cleaned Level 2 event files (see Section 4.7). Starting from the Level 2 files, high-level scientific products (sky images, light-curves and energy spectra) can be extracted. We will see that it is also possible to apply a different data screening which may be more or less conservative than the standard one.

4.3 SAA passages calculation (*'nucalcsaa'*)

The NuSTARDAS software module '*nucalcsaa'* calculates South Atlantic Anomaly (SAA) passages of the NuSTAR observatory.

The task requires in input the following files:

- Housekeeping file (*hkfile*)
- Level 1a event file (*evtfile*)
- Orbit file (*orbitfile*)
- Makefilter configuration file (*mkfconfigfile*)

The file generated in output by the task is:

- Housekeeping file (*outfile)*

The '*nucalcsaa'* module identifies the SAA passage in two different modes: 'STRICT' and 'OPTIMIZED'. The mode to be used can be set through the input parameter *'saamode'*. In the 'STRICT' removal mode the SAA passages are identified by monitoring the level of the high-gain shield singles rates stored in the 'SHLDHI' column of the input housekeeping file. In the 'OPTIMIZED' mode the SAA passages found in the 'STRICT' mode are refined by requiring the presence of an increase of the detector events count rates simultaneous to the observed shield singles rates increase. The results are written in a new column named 'SW_SAA' of the output housekeeping file.

In addition, by setting the input parameter '*tentacle'* to *'yes'*, the task allows identification and flagging of time intervals in which the detector events count rates show an increase. This search is done only when the spacecraft is entering into the SAA region and a simultaneous shield singles rates increase is not required. The results are written in a new column named 'SW_TENTACLE' of the output housekeeping file.

The various numerical values used by the algorithm are stored in a specific CALDB file provided in input through the parameter '*saaparfile*'.

The algorithm has been tested for steady sources with fluxes not dominating over the detector background. The '*tentacle'* option should be used only when the background count rate is not stable and shows time intervals of increased intensity. The users should carefully check the time intervals identified by the task.

Usage example:

1. Calculate the 'SW_SAA' column using the 'OPTIMIZED' SAA removal function. The new column is stored in the ouput file 'nu40060001001A_fpm_out.hk':

```
> nucalcsaa hkfile=nu40060001001A_fpm.hk orbitfile=nu40060001001_orb.fits
  evtfile=nu40060001001A_uf.evt outfile=nu40060001001A_fpm_out.hk
  saamode=OPTIMIZED tentacle=no
```

4.4 Filter File Generation (*'nufilter'*)

The NuSTARDAS software module *'nufilter'* creates a filter file, which is used for the data screening by the *'nuscreen'* module (see next section 4.5). The filter file contains the attitude and orbit derived quantities, the instrument housekeeping parameter values, and the quality of the reconstructed mast position as a function of time.

The task requires in input the following files:

- Housekeeping file (*hkfile*)
- CEB Housekeeping (*cebhkfile*)
- Attitude file (*attfile*)
- Position Sensing Detector file (*psdcorfile*)
- Orbit file (*orbitfile*)
- Makefilter configuration file (*mkfconfigfile*)
- NORAD Two Line Elements (TLEs) file (*tlefile*)

The file generated in output by the task is:

- Filter file (*mkffile*)
- Attitude-orbit file (*attorbfile*)

In the first step, *'nufilter'* derives attitude and orbit related quantities by running the multi-mission '*prefilter*' FTOOL. The satellite attitude information included in the attitude file is interpolated and the NORAD Two Line Elements (TLEs) are propagated to determine satellite ephemeris quantities. This information is used to calculate quantities such as Elevation Angle, Bright Earth Angle, Sun Angle, Cut-off rigidity, etc. The output file of '*prefilter*' (parameter '*attorbfile*') contains the set of columns defined in the CALDB file '*preconfigfile*'.

In the second main step, the *'nufilter'* creates the filter file by running the multi-mission FTOOL *'makefilter'*. The housekeeping information is read from the input orbit file (parameter *'orbitfile'*), the housekeeping files (parameters *'hkfile'* and *'cebhkfile'*) and the spacecraft attitude file (parameter *'attfile'*). The quality of the reconstructed mast position is read from the *'METGRID_FLAG'* column of the position sensing detector file (parameter *'psdcorfile').* The *'makefilter'* configuration file, provided in input through the parameter *'mkfconfigfile'*, is a FITS file (by default read from the CALDB) which contains for each parameter the following information: the parameter name, the name of the FITS file, the name of the extension containing the parameter, the interpolation method, the calibration method, the output parameter name and comments for the corresponding keyword in the output filter file.

The interpolation method is used when the value of a specific parameter is not present at given times; the calibration method is applied when some simple numerical manipulations on the input HK parameters is needed. Currently, the default of the interpolation method is set to copy the last known value of that parameter. The calibration method has not been implemented yet. See also the *'makefilter'* help file for further details.

Usage example:

1. Create the output 'prefilter' file named nu40060001001A.attorb and a filter file named nu40060001001A.mkf in the output directory 'event_cl':

```
> nufilter hkfile=nu40060001001A_fpm.hk attfile=nu40060001001_att.fits
  orbitfile=nu40060001001_orb.fits cebhkfile=nu40060001001A_ceb.hk
  psdcorfile=nu40060001001A_psdcorr.fits outdir=./event_cl pntra=258.3014
  pntdec=-23.7678 tlefile=NUSTAR_TLE_ARCHIVE.txt.2013042
```

4.5 Good Time Intervals Generation and Data Screening (*'nuscreen'*)

The NuSTARDAS software module *'nuscreen'* filters calibrated event files by applying cleaning criteria on specified orbital, attitude and instrument parameters. To this end, specific Good Time Intervals files (GTIs) based on attitude/orbit and instrument housekeeping parameters are generated from the filter file. A data screening based on event properties (e.g. the charge pattern) is also applied to produce the output Level 1 cleaned science event files.

The task requires in input the following files:

- Level 1 event file (*infile*)
- Filter file (*mkffile*)
- Housekeeping Range file (*hkrangefile*)
- Events Range file (*evtrangefile*)
- Housekeeping file (*hkfile*)

The files generated in output by the task are:

- Level 2 science event file (outfile)
- Good Time Interval file (*gtifile*)

The *'nuscreen'* task i) generates a GTI file based on attitude and/or instrument housekeeping parameters and quality of the reconstructed mast position, ii) screens the data using these GTIs, iii) screens events using a GRADE filter and/or a selection on the STATUS column, iv) applies the dead time correction to the temporal keywords of the screened event files.

The GTIs are calculated considering two different sets of parameters, one related to the satellite attitude and orbit (*'createattgti=yes'*) and the other related to instrument housekeeping (*'createinstrgti=yes'*). The GTI file is created by running the multi-mission FTOOL *'maketime'* and contains the time intervals where events are considered good for science data analysis.

Setting the input parameter *'gtiexpr'* to 'DEFAULT' and *'hkrangefile'* to *'CALDB'*, the attitude and instrument housekeeping parameters screening expressions are built using the standard criteria contained in the Housekeeping Calibration files, which are dependent on the observing mode selection provided in input through the parameter '*obsmode*'. The supported observing modes are SCIENCE, OCCULTATION, SLEW, SAA, CALIBRATION and SCIENCE_SC (see Section 2.1). It is possible to supply attitude and/or instrument non-standard criteria through the parameter *'gtiexpr'* providing a specific Boolean expression.

The calculated GTIs are used to screen the events by setting the parameter *'gtiscreen'* to *'yes'* (default value). An additional user created GTI file can also be provided in input by using the *'usrgtifile'* parameter.

'nuscreen' filters out the events previously flagged as "bad" in the 'STATUS' column of the event file (i.e. bad/hot pixels). Moreover, the task applies a grade selection by setting the *'evtscreen'* parameter to *'yes'*. The standard screening criteria for GRADE and STATUS are defined in the Event Range Calibration file and to use these the parameter *'evtrangefile'* is set to CALDB and *'gradeexpr'* and *'statusexpr'* parameters are set to *'DEFAULT'*. Non-standard screening criteria can be specified using the parameters *'gradeexpr'* and *'statusexpr'*. The first is for the selection on the GRADE column and values can be input as a range or a single number (e.g. *'gradeexpr=0-4'* to select GRADE range between 0 and 4; *'gradeexpr=0'* to select only GRADE equal to 0). These inputs are used with the 'filter grade' command in *'xelect'*. The second is

for the selection on the STATUS column and the value should be input as a Boolean expression, e.g. *expr="STATUS==b0"* to select only good events (see Sections 3.4, 3.5 and 3.8 for the definition of the values in the STATUS column).

The parameters *'gtiexpr'* and *'statusexpr'* accept the expression directly from the command line or written into a text file and input by preceding the filename with '@' (e.g. statusexpr=@file.txt). The expression in the file can be arbitrarily complex and can extend over multiple lines of the file. Lines that begin with 2 slash characters (//) are ignored and can be used to add comments.

If all the screening parameters are set to 'yes', the output events file contains only good events and the GTI extension is updated.

'nuscreen' also applies the dead time correction to the temporal keywords of the output screened event files by running the '*nulivetime'* task (see Section 4.6).

Usage Example:

1. Generate the cleaned event file nu40060001001A01_cl.evt (DEFAULT name) and the GTI FITS file nu40060001001A01_gti.fits (DEFAULT name) using the screening expression to create the GTI written in the Housekeeping Range Calibration file and the events selection criteria defined in the Events Range Calibration file:

```
> nuscreen obsmode=SCIENCE infile=nu40060001001A_uf.evt gtiscreen=yes
  evtscreen=yes gtiexpr=DEFAULT gradeexpr=DEFAULT statusexpr=DEFAULT
  createattgti=yes createinstrgti=yes outdir=./event_cl
  hkfile=nu40060001001A_fpm.hk mkffile=nu40060001001A.mkf outfile=DEFAULT
```

4.6 Dead Time Correction (*'nulivetime'*)

The NuSTARDAS software module '*nulivetime'* calculates the dead time corrections necessary to update the temporal keywords of the screened NuSTAR event files. It is run automatically by the *'nuscreen'* task (see previous section).

The task requires in input the following files:

- Level 2 event file (*infile*)
- Housekeeping file (*hkfile*)

The file generated in output by the task is:

- Level 2 event file with updated temporal keywords (*outfile*)

'nulivetime' applies the dead time corrections and updates the temporal keywords of the screened NuSTAR event files. The dead time correction is calculated using information stored in the input file *'hkfile'* and written in the keyword 'DEADC' of the output event file. 'nulivetime' also updates the 'EXPOSURE' and 'LIVETIME' keywords of the output event file.

Usage example:

1. Apply dead time corrections to the input cleaned event file 'nu40060001001A01_cl.evt'.

```
> nulivetime infile=nu40060001001A01_cl.evt hkfile=nu40060001001A_fpm.hk
  outfile=NONE
```

4.7 Screening criteria

In this section we describe the screening criteria associated with i) attitude, orbital and/or instrumental parameters, ii) quality of the reconstructed mast position and iii) specific events properties which are applied by the *'nuscreen'* module to produce Level 2 cleaned event files.

The values of the attitude, orbital and instrumental parameters and the parameter related to the quality of the reconstructed mast position (see next sections), as a function of time are included in the Filter File (*.mkf) and are used to generate Good Time Intervals (GTIs) for which their values are within specified ranges.

4.7.1 Screening Criteria associated with the attitude and orbital parameters

One set of screening criteria is obtained by considering parameters related to the satellite position and the telescopes boresight direction. These parameters are part of the standard screening in *'nuscreen'* (and in the *'nupipeline'* script). Non standard screening expressions can be set through the parameter *'gtiexpr'* (see examples in Section 4.8). The Filter File columns that can be used for the GTIs generation are:

- **SAA_A**, **SAA_B**: South Atlantic Anomaly (for focal plane module A and B, respectively) flags with value '0' (observatory outside the SAA) or '1' (observatory in the SAA);
- **SW_SAA, SW_TENTACLE:** refined South Atlantic Anomaly flags as evaluated by the *'nucalcsaa'* module (see Section 4.3), with value '0' (observatory outside the SAA) or '1' (observatory in the SAA);
- **ELV:** elevation angle between the telescopes boresight and the Earth limb (degrees);
- **OCCULTED**: flag with value '0' (Earth not in the FOV) or '1' (EARTH in the FOV);
- **SLEW**: flag with value '0' (observatory not slewing) or '1' (observatory performing a slew between two targets);
- **SOURCE**: indicates the origin for the reconstruction of the attitude file ('1' = attitude from the star tracker on the Optics Bench "CHU4", used for scientific analysis; '2' = attitude from spacecraft star trackers "CHU123");
- **RESIDUAL:** quality of the attitude reconstruction from the "CHU4" star tracker on the Optics Bench.

4.7.2 Screening Criteria associated with the mast position

For the NuSTAR observatory, a good reconstructed mast position is crucial to evaluate accurate sky coordinates for each event. The Position Sensing Detectors (PSDs) are two optical detectors located in the focal plane to monitor and evaluate the mast position as a function of the time. The PSDs are calibrated only in a specific grid, which is stored in the CALDB metrology grid file. Occasionally, due the mast movements, the laser spots can be outside this calibrated grid and in this case the sky coordinates are not calculated. As a consequence, the corresponding time intervals must be excluded from the GTIs. A specific column, named 'METGRID_FLAG', of the Filter File marks the time intervals when the metrology grid data are valid. This column is used for the GTIs generation and its values are defined as follows:

- **METGRID_FLAG**: the value of this parameter is '0' (laser spot within the grid) or '1' (out of grid)

4.7.3 Screening Criteria associated with the instrumental parameters

Screening on specific instrument parameters is done to ensure that data are always included within certain specific ranges. The *'nuscreen'* software module can handle screening criteria to define GTIs according to specific instrumental housekeeping parameter range values. The instrumental parameters and the optimized range of the Filter File instrumental columns used for the GTIs generation are:

- **CAL0STAT**: flag with value '0' (on-board calibration sources not in FPMA FOV) or '1' (on-board calibration sources in FPMA FOV);
- **CAL1STAT**: flag with value '0' (on-board calibration sources not in FPMB FOV) or '1' (on-board calibration sources in FPMB FOV);
- **LIVETIME:** exposure corrected for the dead time.

4.7.4 Standard Screening Expressions for attitude/orbital/instrumental parameters

The unfiltered NuSTAR Level 1a science event files can be divided in up to six different Level 2 cleaned event files, according to the standard screening on the values of attitude/orbital/instrumental parameters.

Each cleaned event file stores the data taken in one of the supported observational modes (see also Section 2.1) as detailed below:

1. **SCIENCE (01)**: data from the science target with good attitude reconstruction. The following screening expressions are used:
   - `ELV>3 && SAA_A=0 && SAA_B=0 && SW_SAA=0 && SW_TENTACLE=0 && SLEW=0 && SOURCE=1 && RESIDUAL<7 && CAL0STAT=0 && LIVETIME>0 && METGRID_FLAG=0 (for FPMA)`
   - `ELV>3 && SAA_A=0 && SAA_B=0 && SW_SAA=0 && SW_TENTACLE=0 && SLEW=0 && SOURCE=1 && RESIDUAL<7 && CAL1STAT=0 && LIVETIME>0 && METGRID_FLAG=0 (for FPMB)`

2. **OCCULTATION (02)**: data during the Earth occultation. The following screening expressions are used:
   - `ELV<=3 && SAA_A=0 && SAA_B=0 && SW_SAA=0 && SW_TENTACLE=0 && SLEW=0 && CAL0STAT=0 && LIVETIME>0 && METGRID_FLAG=0 (for FPMA)`
   - `ELV<=3 && SAA_A=0 && SAA_B=0 && SW_SAA=0 && SW_TENTACLE=0 && SLEW=0 && CAL1STAT=0 && LIVETIME>0 && METGRID_FLAG=0(for FPMB)`

3. **SLEW (03)**: data taken during a spacecraft slew. The following screening expressions are used:
   - `SAA_A=0 && SAA_B=0 && SW_SAA=0 && SW_TENTACLE=0 && SLEW=1 && CAL0STAT=0 && LIVETIME>0 && METGRID_FLAG=0 (for FPMA)`
   - `SAA_A=0 && SAA_B=0 && SW_SAA=0 && SW_TENTACLE=0 && SLEW=1 && CAL1STAT=0 && LIVETIME>0 && METGRID_FLAG=0 (for FPMB)`

4. **SAA (04)**: data taken during a SAA passage. The following screening expression is used:
   - `(SAA_A=1||SAA_B=1||SW_SAA=1||SW_TENTACLE=1) && (LIVETIME=0 && METGRID_FLAG=0) (for FPMA and FPMB)`

5. **CALIBRATION (05)**: data when the on-board calibration source is in the Field Of View. The following screening expressions are used:
   - `SAA_A=0 && SAA_B=0 && SW_SAA=0 && SW_TENTACLE=0 && CAL0STAT=1 && LIVETIME>0 && METGRID_FLAG=0 (for FPMA)`
   - `SAA_A=0 && SAA_B=0 && SW_SAA=0 && SW_TENTACLE=0 && CAL1STAT=1 && LIVETIME>0 && METGRID_FLAG=0 (for FPMB)`

6. **SCIENCE_SC (06)**: data from the science target with poor attitude reconstruction. The following screening expressions are used:
   - `ELV>3 && SAA_A=0 && SAA_B=0 && SW_SAA=0 && SW_TENTACLE=0 && SLEW=0 && SOURCE=2 && CAL0STAT=0 && LIVETIME>0 && METGRID_FLAG=0 (for FPMA)`
   - `ELV>3 && SAA_A=0 && SAA_B=0 && SW_SAA=0 && SW_TENTACLE=0 && SLEW=0 && SOURCE=2 && CAL1STAT=0 && LIVETIME>0 && METGRID_FLAG=0 (for FPMB)`

4.7.5 Screening Criteria associated with the event proprieties

During data screening additional selections, associated with characteristics of the events themselves, are applied.

The current NuSTAR screening criteria are:

- Removal of events on bad and hot/flickering pixels (*'nuflagbad'* and *'nuhotpix'*, see Sections 3.4 and 3.5)
- Removal of events failing the depth of interaction cut (see *'nuflagevt',* see Section 3.8)
- Removal of events failing the *'*baseline*'*, *'*prior*'* and *'*reset*'* cuts (see *'nuflagevt'* see Section 3.8)
- Removal of events with PI values out of range (*'nuflagevt',* see Section 3.8)
- Grade selection (*'nucalcpha',* see Section 3.6)

These criteria are applied to the data using the information stored in the 'STATUS' column of the event file storing the type of flag according to the following definitions:

- `b0000000000000000 Good event`
- `b0000000000000001 Event falls in a bad pixel from on-ground CALDB Bad Pixel File`
- `b0000000000000010 Event falls in a bad pixel from on-board disabled pixel`
- `b0000000000000100 Event falls in a bad pixel from user bad pixel file`
- `b0000000000001000 Event has a neighbor bad from bad/disabled/user pixel list`
- `b0000000000010000 Event falls in a detector edge pixel`
- `b0000000000100000 Event falls in a hot/flickering pixel`
- `b0000000001000000 Event has a neighbor hot/flickering pixel`
- `b0000000010000000 Event fails depth cut`
- `b0000000100000000 Event fails baseline cut`
- `b0000001000000000 Event fails prior/reset cut`
- `b0000010000000000 Event fails prior cut`
- `b0000100000000000 Event fails reset cut`
- `b0001000000000000 Event with PI out of range`

The standard expression used to filter out for bad events is:

`STATUS = b000000000x0xx000`

This expression excludes from the event file all the flagged events, except i) events having a neighbor bad from bad/disabled/user pixel list, ii) events falling in a detector edge pixel and iii) events having a neighbor hot/flickering pixel.

In addition to the selection on the 'STATUS' column, the events are filtered according to the value of the 'GRADE' column. A single X-ray event can in fact be spread in more than one detector pixel (up to 4 contiguous pixels). The grade is a classification of the shape of X-ray events on the detector. The single pixel events (i.e. grade 0) have better spectral resolution than others. Single or double pixel events are more likely to be X-ray events than three-four pixel events. There are 32 grades defined for NuSTAR (as described in Chapter 3) and their values are stored in the 'GRADE' column of the event file.

The standard grade selection defined by the NuSTAR Calibration Team and stored in the CALDB is:

```
GRADE ≥ 0 && GRADE ≤ 26.
```

4.7.6 SCIENCE observational mode: summary.

The observing mode "**SCIENCE"** (01) is the mode used for the extraction of high-level scientific products. The standard screening criteria used to generate cleaned Level 2 "01" event files in the archive for this observing mode is summarized below:

1. Removal of the following time intervals:
    - During a slew of the satellite;
    - When the Earth is in the Field Of View;
    - When the satellite is in the South Atlantic Anomaly;
    - When the angle between telescope boresight and Earth limb is equal or less than 3 deg;
    - When the on-board calibration source is in the Field Of View;
    - When the attitude reconstruction is not derived from the star tracker mounted on the Optics Bench;
    - When the quality of the attitude reconstruction from the star tracker on the Optics Bench is low (RESIDUAL > 7);
    - When either of the laser spots tracking the mast motion are outside the PSD calibrated grid;
    - When the LIVETIME is zero.
2. Removal of bad pixels (dead, hot and flickering), events failing the depth/baseline/prior/reset cuts, events with PI channels out of range.
3. The grade of the event in the range 0-26.

4.8 Examples of how to screen the data with custom selections

The following two equivalent methods allow performing customized screening:

1. By running the *'nuscreen'* script (see Section 4.5) specifying screening criteria via the input parameters *'gtiexpr '*, *'gradeexpr'*, and *'statusexpr'*.

2. By running the Stage 2 of the *'nupipeline'* script. Within *'nupipeline',* the screening criteria are specified by the values of the input parameters *'gradeexpr'*, *'statusexpr'* and *'gtiexpr01'*, *'gtiexpr02'*,

'gtiexpr03', *'gtiexpr04'*, *'gtiexpr05'*, 'gtiexpr06*'*. Note that by default (parameter *'obsmode=ALL'*) the *'nupipeline'* runs the *'nuscreen'* module six times.

4.8.1 Example of how to use *'nuscreen'*

For detailed spectral analysis it could be necessary to optimize the energy resolution. To this aim, users can decide to select only events with grades equal to '0' (single pixel events) starting from the Level 2 event file. The command line to be used is:

```
> nuscreen infile=nu40060001001A01_cl.evt gtiscreen=no evtscreen=yes
  gtiexpr=NONE gradeexpr=0 statusexpr=NONE outdir=./
  hkfile=nu40060001001A_fpm.hk outfile=nu40060001001A01_cl_grade0.evt
```

In this example the GTIs are not applied, by setting the *'gtiscreen'* parameter to *'no'*, since the input event file was already cleaned. The grade selection is done setting the parameter *'evtscreen'* to yes. The parameter *'gradeexpr'* specifies the values to filter in the column 'GRADE'.

4.8.2 Example of how to use nupipeline

The above example above can also be handled by *'nupipeline'*. In this case both Stage 1 and Stage 2 are executed and the command to be used is:

```
> nupipeline indir=./40060001001 outdir=./event_cl steminputs=nu40060001001
  obsmode=SCIENCE instrument=FPMA evtscreen=yes gradeexpr=0
```

4.9 Generation of Exposure Maps (*'nuexpomap'*)

The NuSTARDAS software module *'nuexpomap'* generates Sky Exposure Maps storing, for a given observation, the net exposure time for each sky pixel. The exposure map accounts for detector bad and hot pixels, detector gaps, attitude variations, mast movements and, optionally, telescope vignetting.

The task requires in input the following files:

- Level 2 event file (FITS file)
- Attitude file (FITS file)
- Mast Aspect Solution file (FITS file)
- DET1 Reference Point file (FITS file)

The file generated in output by the task is:

- Exposure Map file (FITS file)

The NUSTARDAS *'nuexpomap*' task first generates a set of instrument maps in Focal Plane Bench DET1 frame where bad/hot pixels and detector gaps are marked using information from the 'BADPIX' extension of the input event file (parameter *'infile'*) and from the input CALDB Instrument Probability Map File (parameter *'instrprobmapfile'*), respectively.

The set of DET1 instrument maps is constructed as follows. First, the task reads the input file *'det1reffile'* storing the X/Y SKY position as a function of time of a reference pixel in the DET1 coordinate system. Second, the X/Y offsets relative to their minimum value in the *'det1reffile'* are calculated. Third, the X/Y offsets are binned with a bin size in pixels specified by the input parameter *'pixbin'*. Each bin defines a time interval during which the spatial fluctuations due to attitude variations and mast movements are below the *'pixbin'* value and are considered constant. This information is then used by *'nuexpomap'* to build the aspect histogram defining, for each spatial offset bin, the time interval and duration of each single DET1 instrument map. By setting the parameters *'offsetfile'* and *'aspecthistofile'* to something other then *'NONE'* the task saves in the current directory the spatial offset and aspect histogram files, respectively.

Each DET1 instrument map is then transformed to the Optics Bench DET2 frame using the mast aspect solution (parameter *'mastaspectfile'*) and the CALDB align file (parameter *'alignfile'*). In this step, *'nuexpomap'* makes use of the multi-mission FTOOLs *'combinexform'* and *'imagetrans'*.

Optionally, if the parameter *'vignflag'* is set to *'yes'*, the task applies the vignetting correction to the DET2 instrument maps using the vignetting CALDB file (parameter *'vignfile'*). The vignetting correction is applied at the energy value specified by the parameter *'energy'*.

Next, the DET2 instrument maps are transformed to the SKY frame using the attitude information provided in input through the parameter *'attfile'*. To this end, the multi-mission FTOOLs *'getxform', 'imagetrans'* and *'getwcs'* are used by *'nuexpomap'*. The total exposure map, storing in each pixel the net exposure time of the observation, is then calculated by summing the single exposure maps in sky coordinates. Dead time corrections are included in the total exposure map.

By setting the parameters *'det1instrfile'*,*'det2instrfile'* and *'skyinstrfile'* to something other then *'NONE'* the task saves in the current directory the single DET1, DET2 and SKY instrument maps as FITS IMAGE extensions in the corresponding output files.

Optionally, the task allows the generation of smaller exposure maps covering a user defined region of the SKY grid, as defined by the input parameters '*skyx*', '*skyy*' and '*skysize*'. In this case *'nuexpomap'* uses the task '*nuskytodet*' to transform *'skyx'* and *'skyy'* in the DET1 and DET2 coordinates, needed to generate the exposure maps.

Usage Examples:

1. Generate the exposure map nu40060001001A01_ex10.img including the vignetting correction at energy 10 keV (default), starting from the Level 2 event file nu40060001001A01_cl.evt. The command line to be used is:

```
> nuexpomap infile=nu40060001001A01_cl.evt attfile=nu40060001001_att.fits
  mastaspectfile=nu40060001001_mast.fits det1reffile=nu40060001001_det1.fits
  expomapfile=nu40060001001_ex10.img
```

2. The vignetting correction can be applied to the exposure maps at an energy different from the default value, by setting the value of the parameter *'energy'*. In the example below the energy used for the vignetting correction is 30 keV.

```
> nuexpomap infile=nu40060001001A01_cl.evt attfile=nu40060001001_att.fits
  mastaspectfile=nu40060001001_mast.fits det1reffile=nu40060001001_det1.fits
  expomapfile=nu40060001001_ex30.img energy=30
```

3. The exposure map can be also generated without applying the vignetting correction, starting from the Level 2 event file nu40060001001A01_cl.evt. In this case the command line to be used is:

```
> nuexpomap infile=nu40060001001A01_cl.evt attfile=nu40060001001_att.fits
  mastaspectfile=nu40060001001_mast.fits det1reffile=nu40060001001_det1.fits
  expomapfile=nu40060001001_ex_no_vig.img vignflag=no
```

4.9.1 Exposure maps generation in 'nupipeline'

The exposure map for the '01' observation mode (i.e. "SCIENCE") can be directly generated when running the *'nupipeline'* script by setting the parameter *'createexpomap'* to *'yes'* (default value is *'no'*), as illustrated in the following examples.

Usage examples:

1. The results of *'nuexpomap'* in Example 1 of section 4.9, can be reproduced by running '*nupipeline'* as follows:

```
> nupipeline indir=./40060001001 outdir=./event_cl steminputs=nu40060001001
  obsmode=SCIENCE instrument=FPMA createexpomap=yes
```

2. The results of *'nuexpomap'* in Example 2 of section 4.9, can be reproduced by running '*nupipeline'* as follows:

```
> nupipeline indir=./40060001001 outdir=./event_cl steminputs=nu40060001001
  obsmode=SCIENCE instrument=FPMA createexpomap=yes energy=30
```

3. The results of *'nuexpomap'* in Example 3 of Section 4.9, can be reproduced by running '*nupipeline'* as follows:

```
> nupipeline indir=./40060001001 outdir=./event_cl steminputs=nu40060001001
  obsmode=SCIENCE instrument=FPMA createexpomap =yes expovignflag=no
```

4.10 Trasformation of SKY coordinates in DET1 and DET2 coordinates (*'nuskytodet'*)

The NUSTARDAS '*nuskytodet*' calculates as a function of time the Focal Plane Bench Frame coordinates (DET1) and the Optics Bench Frame coordinates (DET2) of an input position in SKY coordinates.

The task requires in input the following files:

- Attitude file (FITS file)
- Mast Aspect Solution file (FITS file)
- DET1 Reference Point file (FITS file)

The file generated in output by the task is:

- SKY Reference Pixel File in DET1 and DET2 system (FITS file)

'*nuskytodet*' reads the input SKY coordinates from the parameters '*skyxref*' and '*skyyref*'. The tranformations from SKY to DET1 and DET2 frames are calculated using information from the attitude file (*'attfile'*), the mast aspect solution file ('*mastaspectfile*') and the two CALDB files '*teldef*' and '*align*'. The DET1 and DET2 values as a function of time are stored in the output file '*skydetfile*'.

Usage Examples:

1. Calculate the DET1 and DET2 coordinates of the SKY pixel (X,Y)=(500,500) and store them in the output file 'nu40060001001A_skydet.fits'.

```
> nuskytodet instrument=FPMA mastaspectfile=nu40060001001_mast.fits
  attfile=nu40060001001_att.fits pntra=258.3014 pntdec=-23.7678
  skydetfile=nu40060001001A_skydet.fits
```

5 EXTRACTION OF PRODUCTS (STAGE 3)

This chapter describes Stage 3 of the NuSTAR data reduction, which is dedicated to the generation of high-level scientific products (light-curves, energy spectra, sky images, ARF and RMF files).

The inputs to Stage 3 are the Level 2 cleaned and calibrated event files and other files generated during the previous processing stages. Stage 3 produces in output the Level 3 data products to be used for scientific analysis.

In the following sections the Stage 3 NuSTAR software modules are presented in the same order used for the standard data processing along with software usage examples. These processing steps are coded in a dedicated script named *'nuproducts'* which constitutes the third stage of the *'nupipeline'* script.

Examples of how to execute Stage 3 automatically for standard data processing are illustrated in the next two sections.

The list of the Stage 3 software modules is the following:

- *nuproducts* - Extract high-level data products from a Level 2 event file
- *nubackscale* - Apply backscale correction to energy spectra (called by *'nuproducts'*)
- *nulccorr* - Apply livetime, PSF/EXPOSURE and vignetting corrections to light-curves (called by *'nuproducts'*)
- *numkarf* - Generates an ARF file for an input PHA file (called by *'nuproducts'*)
- *numkrmf* - Generates an RMF file for an input spatial region file (called by *'nuproducts'*)

The following Level 3 data products are generated during this stage:

- Source energy spectrum
- Background energy spectrum
- Redistribution Matrix File (RMF)
- Ancillary Response File (ARF)
- Source light-curve
- Background light-curve
- Field image in sky coordinates

The level 3 NuSTAR files are FTOOLS compliant and users can perform spectral analysis by using the *XSPEC* package and temporal analysis with the *LCURVE* or *XRONOS* software packages (see `http://heasarc.gsfc.nasa.gov/docs/xanadu/xanadu.html`).

5.1 Standard Data Processing with *'nuproducts'* (Stage 3)

To apply the data reduction steps for the extraction of high-level scientific products the *'nupipeline'* task makes use of a dedicated script named *'nuproducts'* (see Section 5.3). The *'nuproducts'* scripts automatically retrieves all the necessary input files from a directory specified by the input parameter *'indir'* which must be set to the output directory of a previous run of *'nupipeline'* (Stages 1 and 2). An example of a standard command line for a point-like source is:

```
> nuproducts indir =./event_cl instrument=FPMB steminputs=nu40060001001
  outdir=./products srcregionfile=source.reg bkgregionfile=background.reg
```

In this case *'nuproducts'* is run from the same directory used to execute the *'nupipeline'* run (*event_cl* in the various command line examples) and generates in the *'products'* directory the source energy spectrum, background energy spectrum, RMF file, ARF file, corrected source light-curve, corrected background light-curve, and field image in sky coordinates for the FPMB module. The source and background extraction regions are read from the input ASCII files *'source.reg*' and *'background.reg*', respectively. These files should have a format compatible with *XSELECT* and *DS9*.

5.2 Standard Data Processing with *'nupipeline'* (Stages 1, 2 and 3)

The data reduction steps for the extraction of high-level scientific products are also coded in the third stage of the *'nupipeline'* script which directly runs the *'nuproducts'* module. This can done by setting the input parameter *'exitstage=3'*. In this case the *'nupipeline'* script, in a single command line, applies to the data the calibration steps (Stage 1), the screening steps (Stage 2) and extracts the high-level data products (Stage 3). By default, data from both modules (FPMA and FPMB) are processed.

The standard command line to be used is:

```
> nupipeline indir=/archive/40060001001/ steminputs=nu40060001001
  outdir=./event_cl exitstage=3 srcregionfile=source.reg
  bkgregionfile=background.reg
```

5.3 The Extraction of high-level data products (*'nuproducts'*)

The NUSTARDAS module '*nuproducts*' is a perl script, which utilizes the *XSELECT* multi-mission software package to extract source and background light-curves and energy spectra from the input calibrated and screened event files (Level 2). By default, *'nuproducts'* calls the '*numkrmf*' and '*numkarf*' tasks to generate the RMF and/or ARF files appropriate for the spectral analysis.

The '*nuproducts*' task also updates the values of the keywords 'BACKFILE', 'RESPFILE' and 'ANCRFILE' with the names of the background spectrum file, the RMF file and the ARF file, respectively. For spectral analysis (e.g. by using *XSPEC*), users should decide on grouping or not the source spectrum using an external tool (e.g. by using the FTOOL '*grppha*'). By default, *'nuproducts'* calls the *'nulccorr'* task, to apply various corrections to the output light-curves, and the *'nubackscale'* task to apply backscale corrections to the output energy spectra.

The input parameters needed to run *'nuproducts'*, are the Right Ascension and Declination of the source (i.e. parameters '*srcra'* and '*srcdec'*), the Right Ascension and Declination of the center of the background region (i.e. parameters '*bkgra'* and '*bkgdec'*), or alternatively, the source and background extraction region files. Also, the data input directory, the stem for FITS input files, the chosen NuSTAR detector (FPMA or FPMB) and the output directory for the generation of the products, must be specified.

The task requires in input the following files:

- Level 2 event file (FITS file)
- Source region file (ASCII file)
- Background region file (ASCII file)
- Attitude file (FITS file)
- Mast Aspect Solution file (FITS file)
- DET1 Reference Point file (FITS file)
- Optical Axis file (FITS file)
- Housekeeping file (FITS File)

The files generated in output are the following:

- Source spectrum (FITS file and gif)
- Source corrected light-curve (FITS file and gif)
- Source image (FITS file and gif)
- Background spectrum (FITS file)
- Background corrected light-curve (FITS file)
- Response Matrix file (FITS file)
- Ancillary Response file (FITS file)

The source spectrum and light-curve are extracted by filtering the data on a spatial region in SKY coordinates. If the parameter *'srcregionfile'* is set to '*DEFAULT'* it is possible, through the parameters *'srcra'*, *'srcdec'* and *'srcradius'*, to specify the Right Ascension and Declination of the center and the radius of a circular extraction region. A region file with an arbitrary shape can be input through the parameter *'srcregionfile'*. This file should have a format compatible with *XSELECT* and *DS9*. A full field of view image in sky coordinates is produced if the parameter *'imagefile'* is different from *'NONE'*. **Note that energy spectra and light-curves are not background subtracted at this point.**

By setting the parameter *'bkgextract'* to *'yes'* (default value) it is possible to extract the spectrum and light-curve of the background from a region file specified by the parameter *'bkgregionfile'*. Alternatively (*'bkgregionfile'='DEFAULT'*), it is possible to define through the parameters *'bkgra'*, *'bkgdec'*, *'bkgradius1'* and *'bkgradius2'* the Right Ascension, Declination of the center and the inner and outer radii of an annular extraction region.

If the input parameter '*runbackscale*' is set to 'yes' (default), the 'BACKSCAL' keywords of the source and background energy spectra are updated by running the '*nubackscale'* task (see Section 5.5).

By default (parameter '*correctlc=yes'*), the task applies the livetime, PSF/EXPOSURE and vignetting corrections to the output source light-curves by running the '*nulccorr'* task (see Section 5.6). In the case of background light-curve only livetime and EXPOSURE corrections are applied.

For the extraction of light-curves it is possible set the binsize (in seconds) via the parameter *'binsize'*. For the extraction of light-curves the minimum and maximum values of the PI channels can be changed via the parameters *'pilow'* and *'pihigh'*. Moreover, it is possible to apply a user defined temporal filter to the event file providing in input a FITS GTI file (parameter *'usrgtifile'*).

By setting the parameter *'plotdevice'* to GIF or PS, it is possible to choose the device for plotting the generated image, light curve and spectrum.

Optionally, by setting the input parameters *'rummkarf'* and *'runmkrmf'* to *'yes'* (default value), the task also generates the ARF and RMF files appropriate for the spectral analysis of the source energy spectrum. This is achieved by running the tasks '*numkarf*' and 'numkrmf' (see Sections 5.7 and 5.8, respectively).

Usage examples

Point-like source case:

5.3A. Default Circular and annular extraction regions for source and background:

```
> nuproducts indir =./event_cl instrument=FPMB steminputs=nu40060001001
  outdir=./products srcra=187.2779154 srcdec=2.0523883 bkgra=187.2779154
  bkgdec=2.0523883
```

In this example *nuproducts* generates in the output directory the following data products:

- source energy spectrum (pha file), extracted in circular region centered on *srcra* and *srcdec* with radius of 20 software pixels (parameter *srcradius*). The 'BACKSCAL' keyword in the source spectrum is updated for the exposure variations within the extraction region.
- background energy spectrum (pha file), extracted in annular region centered on *bkgcra* and *bkgdec* with inner and outer radius of 50 (parameter *bkgradius1*) and 80 (parameter *bkgradius2*) software pixels, respectively. The 'BACKSCAL' keyword in the background spectrum is updated for the exposure variations within the extraction region.
- RMF file, appropriate for the source energy spectrum.
- ARF file, appropriate for the point-like source spectrum.
- Source light-curve (not background subtracted) corrected for the livetime, the PSF and vignetting corrections, applied at energy *'lcenergy'* =10 keV .
- Background light-curve (corrected for the livetime and EXPOSURE corrections).
- Field image in sky coordinates.

5.3B. It is also possible to use source and/or background extraction region geometries different from circular and annular ones, respectively. In this case the region files with an arbitrary shape can be input through the parameters '*srcregionfile'* and/or *'bkgregionfile',* respective*ly.* However, note that the task *'numkarf'* supports only circular, elliptical and annular extraction regions centered on the source. Moreover *'numkarf'* only applies the ghost-ray correction (parameter *'grflag'*) for point-like sources (parameter *'extended=no'*) and for circular extraction regions for the source:

```
>  nuproducts indir =./event_cl instrument=FPMB steminputs=nu40060001001
   outdir=./products srcregionfile=source.reg bkgregionfile=background.reg
   lcfile=NONE bkglcfile=NONE imagefile=NONE
```

In this example *nuproducts* generates in the output directory the following data products:

- source energy spectrum (pha file), extracted in the region *source.reg*. The 'BACKSCAL' keyword of the source spectrum is updated for the exposure variations within the extraction region.
- background energy spectrum (pha file), extracted in the region *background.reg*. The 'BACKSCAL' keyword of the background spectrum is updated for the exposure variations within the extraction region.
- RMF file (appropriate for the source spectrum),
- ARF file (for a point-like source spectrum).

5.3C. It is also possible to apply a time filter to the event file and to the high-level data products by providing an input FITS GTI (Good time interval) file (parameter *'usrgtifile'*):

```
> nuproducts indir =./event_cl instrument=FPMB steminputs=nu40060001001
  outdir=./products srcregionfile=source.reg bkgregionfile=background.reg
  usrgtifile=myGTIs.fits
```

5.3D. To analyze light-curves in a specific energy range and temporal bin size, it is necessary to set the values of the parameters '*pilow'* and '*pihigh',* which define the minimum and maximum value of the PI to be included in the extracted light curve, and the parameter *binsize:*

```
> nuproducts indir =./event_cl instrument=FPMB steminputs=nu40060001001
  phafile=NONE outdir=./products srcregionfile=source.reg bkgextract=no
  bkglcfile=NONE imagefile=NONE runmkarf=no runmkrmf=no pilow=100
  pihigh=1000 binsize=500 lcnergy=5
```

In this example *nuproducts* generates in the directory products only the source light-curve extracted using the spatial region *source.reg*, the energy range 100-1000 (in PI channels) and with a temporal bin size of 500 s. The source light-curve, not background subtracted, is corrected for the livetime and the PSF and vignetting corrections are applied at energy 5 keV.

Extended sources case.

In the case of an extended source the Point Spread Function and Ghost-Rays corrections are not applied to the output ARF file. The correction terms include the vignetting, the aperture stop, the detector absorption and the EXPOSURE corrections. To generate the ARF appropriate for an extended source, the value of the parameters *'extended'* must be set to *'yes'* (default value is *'no'*).

5.3E.

```
> nuproducts indir =./event_cl instrument =FPMB steminputs=nu40060001001
  outdir=./products srcregionfile=source.reg bkgregionfile=background.reg
  lcfile=NONE bkglcfile=NONE imagefile=NONE extended=yes grflag=no
  psfflag=no
```

In this example *nuproducts* generates in the output directory the following files:

- source energy spectrum (pha file), extracted in the region *source.reg*. The 'BACKSCAL' keyword of the source spectrum is updated for the exposure variations within the extraction region.
- background enegy spectrum (pha file), extracted in the region *background.reg*. The 'BACKSCAL' keyword of the background spectrum is updated for the exposure variations within the extraction region.
- RMF file (appropriate for the source spectrum).

- ARF file (for the extended source spectrum).

5.4 The Extraction of high-level data products with 'nupipeline'

The *'nuproducts'* script for the extraction of high-level products is coded in the third stage of the *'nupipeline'* script. Therefore by using *'nupipeline'* setting the parameter *'exitstage'* to *'3'*, the script calls *'nuproducts'* and extracts the high-level data products. In the examples given below the same numbering of the previous section is used.

Usage examples:

5.4A.

```
> nupipeline indir=./40060001001 outdir=./event_cl
steminputs=nu40060001001 srcra=187.2779154 srcdec=2.0523883
obsmode=SCIENCE instrument=FPMB exitstage=3 bkgra=187.2779154
bkgdec=2.0523883
```

5.4B.

```
> nupipeline indir=./40060001001 outdir=./event_cl
steminputs=nu40060001001 obsmode=SCIENCE instrument=FPMB exitstage=3
srcregionfile=source.reg bkgregionfile=background.reg fpmb_lcfile=NONE
fpmb_bkglcfile=NONE fpmb_imagefile=NONE
```

5.4C.

```
> nupipeline indir=./40060001001 outdir=./event_cl
steminputs=nu40060001001 obsmode=SCIENCE instrument=FPMB exitstage=3
srcregionfile=source.reg bkgregionfile=background.reg
usrgtifile=myGTIs.fits
```

5.4D.

```
> nupipeline indir=./40060001001 outdir=./event_cl
steminputs=nu40060001001 obsmode=SCIENCE instrument=FPMB exitstage=3
srcregionfile=source.reg bkgextract=no fpmb_phafile=NONE
fpmb_bkglcfile=NONE fpmb_imagefile=NONE runmkarf=no runmkrmf=no pilow=100
pihigh=1000 binsize=500
```

5.4E. (EXTENDED SOURCES):

```
> nupipeline indir=./40060001001 outdir=./event_cl
steminputs=nu40060001001 obsmode=SCIENCE instrument=FPMB exitstage=3
srcregionfile=source.reg bkgregionfile=background.reg fpmb_lcfile=NONE
fpmb_bkglcfile=NONE fpmb_imagefile=NONE extended=yes psfflag=no
arfgrflag=no
```

5.5 Apply backscale correction to energy spectra (*'nubackscale'*)

The NuSTARDAS software module *'nubackscale'* generates a corrected source and/or background spectrum accounting for the exposure variations within the extraction regions. The corrections are calculated using the sky exposure map generated internally by the '*nuexpomap*' task. The task generates output FITS PHA files ('*srcoutfile*' and/or '*bkgoutfile*') with updated values of the 'BACKSCAL' keyword.

The task requires in input the following files:

- source spectrum PHA file (FITS file)
- background spectrum PHA file (FITS file)
- Level 2 event file (FITS file)
- Attitude file (FITS file)
- Mast Aspect Solution file (FITS file)
- DET1 Reference Point file (FITS file)

The files generated in output by the task is:

- source spectrum PHA file (FITS file)
- background spectrum PHA file (FITS file)

This module is called by the *'nuproducts'* script.

Usage example:

1. In this example *'nubackscale'* will update, with the backscale correction, the BACKSCAL keyword of the input source and background spectra: '*nu40060001001A01_sr.pha'* and '*nu40060001001A01_bkg.pha'*, respectively:

```
> nubackscale evtfile= nu40060001001A01_cl.evt
  srcphafile=nu40060001001A01_sr.pha attfile=nu40060001001A01_att.fits
  det1reffile= nu40060001001A01_det1.fits
  mastaspectfile=nu40060001001A01_mast.fits
  bkgphafile=nu40060001001A01_bkg.pha srcoutfile=NONE bkgoutfile=NONE
```

2. Using this command line, *'nubackscale'* applies the backscale correction to the input source and background spectra. The corrected spectra are written in the output files *'nu40060001001A01_sr_corr.pha*' and *'nu40060001001A01_bk_corr.pha'*:

```
> nubackscale evtfile= nu40060001001A01_cl.evt
  srcphafile=nu40060001001A01_sr.pha attfile=nu40060001001A01_att.fits
  det1reffile= nu40060001001A01_det1.fits
  mastaspectfile=nu40060001001A01_mast.fits
  bkgphafile=nu40060001001A01_bkg.pha srcoutfile=nu40060001001A01_sr_corr.pha
  bkgoutfile=nu40060001001A01_bkg_corr.pha
```

5.6 Apply livetime, PSF/EXPOSURE and vignetting corrections to light-curves (*'nulccorr'*)

The NuSTARDAS software module *'nulccorr'* generates a corrected light-curve accounting for the livetime, the PSF/EXPOSURE and vignetting corrections. The livetime correction is always applied and it is calculated using the values of the 'LIVETIME' column in the input file '*hkfile'*.

The task requires in input the following files:

- Light curve file (FITS file)
- Spectrum pha file (FITS file)
- Optical Axis File (FITS file)
- Level 2 event file (FITS file)
- Attitude file (FITS file)
- Mast Aspect Solution file (FITS file)
- DET1 Reference Point file (FITS file)
- Instrument Housekeeping File (FITS file)

The file generated in output by the task is:

- light curve file (FITS file)

For point-like sources (parameter *'extended=no'*), the task applies to the output light-curve the PSF and vignetting corrections by setting the input parameters '*psfflag*' and '*vignflag*' to 'yes' (default values), respectively. The PSF term includes the corrections for the fraction of photons falling outside the light-curve extraction region and for bad pixels and detector gaps located within the extraction region. The vignetting and PSF corrections are applied using the energy value specified by the parameter '*energy*'.

For extended sources (parameter *'extended=yes'*), the task applies to the output light-curve the EXPOSURE and vignetting corrections when setting the input parameters '*expoflag*' and '*vignflag*' to 'yes' (default values), respectively. The EXPOSURE correction term accounts for bad pixels and detector gaps located within the extraction region. Also in this case, the vignetting correction is applied using the energy value specified by the parameter '*energy*'.

The task generates an output FITS light curve ('*outlcfile*') with the 'RATE' and 'ERROR' columns corrected for the different factors. The original values of the 'RATE' and 'ERROR' columns are saved and stored in the two new columns 'RATE_ORIG' and 'ERROR_ORIG' of the output light-curve.

The task also adds or updates to the output light-curve the keyword 'NULCCO' with value 'T' to specify that the light-curve has been corrected.

This module is called by the *'nuproducts'* script.

Usage examples:

1. In this example *'nulccorr'* applies the livetime, PSF and vignetting corrections at energy 10 keV to the input light curve:

```
> nulccorr evtfile=nu40060001001A01_cl.evt outlcfile=NONE
  srcphafile=nu40060001001A01_sr.pha attfile=nu40060001001A01_att.fits
  det1reffile= nu40060001001A01_det1.fits
  mastaspectfile=nu40060001001A01_mast.fits
```

2. The energy of PSF and vignetting corrections can be specified by the parameter *'energy'*. In the example below *'nulccorr'* applies the correction at an energy of 5 keV:

```
> nulccorr evtfile=nu40060001001A01_cl.evt outlcfile=NONE energy=5
  srcphafile=nu40060001001A01_sr.pha attfile=nu40060001001A01_att.fits
  det1reffile= nu40060001001A01_det1.fits
  mastaspectfile=nu40060001001A01_mast.fits
```

3. **Extended source**: in this case the light-curve is corrected for the EXPOSURE variations (i.e. detectors edges/gaps, bad/hot pixel), but no PSF correction is applied. The parameter *'extended'* has to be set to *'yes'* for the extended case, as in the example below:

```
> nulccorr evtfile=nu40060001001A01_cl.evt outlcfile=NONE
  srcphafile=nu40060001001A01_sr.pha attfile=nu40060001001A01_att.fits
  det1reffile= nu40060001001A01_det1.fits
  mastaspectfile=nu40060001001A01_mast.fits extended=yes
```

4. Background light curve: in this case the light curve should be corrected only for the livetime and EXPOSURE variations. The command line to be used for a background light-curve is:

```
> nulccorr evtfile=nu40060001001A01_cl.evt outlcfile=NONE
  srcphafile=nu40060001001A01_sr.pha attfile=nu40060001001A01_att.fits
  det1reffile= nu40060001001A01_det1.fits
  mastaspectfile=nu40060001001A01_mast.fits extended=yes vignflag=no
```

5.7 Generation of ARF files (*'numkarf'*)

The NuSTARDAS software module *'numkarf'* generates an OGIP-style Ancillary Response File (ARF) for an input PHA file, which has been extracted by *'nuproducts'* or *'nupipeline'* or *XSELECT*.

The task requires in input the following files:

- Source spectrum PHA file (FITS file)
- Source region file (ASCII file)
- Optical Axis File (FITS file)
- Level 2 event file (FITS file)
- Attitude file (FITS file)
- Mast Aspect Solution file (FITS file)
- DET1 Reference Point file (FITS file)
- CALDB ARF File (FITS file)

The task generates in output the following file:

- ARF file (FITS file)

'numkarf' generates an OGIP-style Ancillary Response Function (ARF) file which is suitable for input into the spectral fitting program *XSPEC*. The ARF file contains the effective area of the telescope as a function

of energy needed to perform spectral analysis. This is calculated by correcting the input CALDB ARF file, storing the effective area of a source located on-axis without Point Spread Function (PSF) losses.

The input CALDB ARF file is modified taking into account the vignetting, the aperture stop, the ghost rays, the detector absorption and the PSF corrections. These terms, which are functions of the energy, are dependent on the source off-axis angle and azimuth angle. The PSF and ghost rays corrections are also dependent on the radius of the PHA file extraction region. The PSF correction term also includes the corrections for the exposure map such as detector gaps and mast/attitude variations.

The input files for on-axis effective area, PSF, aperture stop, ghost rays, detector absorption and vignetting are, by default, read from the Calibration Database (CALDB). For the PSF files, the CALDB stores a set of files which are energy dependent. The association between energy and CALDB PSF files is specified in the CALDB PSF Grouping File provided in input through the parameter '*grppsffile*'.

The time dependent off-axis angle, azimuth value and distance between the optical axis and the aperture stop center are calculated using the position of the telescope optical axis and of the aperture stop center stored in the input file '*optaxisfile*' (see '*nuskypos*' and '*nucoord*' help files), and written in the output file '*offaxisfile'*.

The distributions of off-axis and azimuth angles for the vignetting correction are stored in the output file '*offaxishisto'*. The distributions of off-axis, azimuth angles and distance between the optical axis and the aperture stop center for the aperture stop and ghost rays corrections are stored in the output files '*apstophisto*' and '*grhisto*' files, respectively.

The vignetting, aperture stop, ghost rays and PSF corrections are calculated, taking into account the source off-axis and azimuth angle distributions, by a weighted mean of the input CALDB values.

If parameters '*psfflag*', '*apstopflag*', '*grflag*', '*detabs*' and '*vignflag*' are set to '*yes'*, the PSF, the aperture stop, the ghost rays, the detector absorption and the vignetting corrections are applied to the input ARF file, respectively. Note that the ghost rays correction is supported only for point-like sources (parameter '*extended*=no') and for source circular extraction regions.

The source position and the radius of the extraction region is read from the input spectrum (parameter '*phafile*') in the 'REG00101' extension. Circular, elliptical and annular extraction regions centred on the source are supported by the task. Only for the detector absorption correction, the source extraction region is read from the input parameter '*srcregionfile*'.

The task can also generate the ARF file for extended sources, such as clusters of galaxies or supernova remnants, by setting the parameter '*extended*' to *'yes'*. To follow the spatial variations of the detector properties for the extended source case, the extraction region file, read from the first extension of the input spectrum file, is divided in boxes of size chosen by setting the parameter '*boxsize*'. For each sub-region, an ARF is produced with the vignetting correction, the aperture stop correction and the detector absorption correction, but without including the point-like PSF correction. This set of ARF files are then combined using the '*addarf*' FTOOL to produce the output ARF.

This module is called by the *'nuproducts'* script.

Usage examples:

1. In this example *numkarf* generates the ARF suitable for the point-like spectrum *nu40060001001A01_sr.pha* extracted by using the circular region *source.reg*. The ARF is corrected for the PSF, the aperture stop, the ghost rays, the detector absorption and the vignetting factors. If the source extraction region *source.reg* is not circular, the ghost rays correction is not applied to the output ARF file:

```
> numkarf infile=nu40060001001A01_cl.evt phafile= nu40060001001A01_sr.pha
  outfile=nu40060001001A01_sr.arf optaxisfile=nu40060001001B_oa.fits
  det1reffile=nu40060001001B_det1.fits srcregionfile=source.reg
```

```
mastaspectfile=nu40060001001_mast.fits attfile=nu40060001001_att.fits
offaxisfile=NONE offaxishisto=NONE grhisto=NONE apstophisto=NONE
```

2. **Extended source**: in this case the ARF cannot be corrected for the PSF and ghost-rays, and only the aperture stop, the detector absorption and the vignetting corrections are applied. To generate the ARF appropriate for an extended source, the value of the parameter *'extended'* has to be set to 'yes' .

   Assuming that *nu40060001001A01_sr.pha* is the spectrum of the extended source extracted by using the region file *source.reg*, the command line to be used is:

```
> numkarf infile=nu40060001001A01_cl.evt srcregionfile=source.reg phafile=
  nu40060001001A01_sr.pha outfile=nu40060001001A01_sr.arf
  optaxisfile=nu40060001001B_oa.fits det1reffile=nu40060001001B_det1.fits
  offaxisfile=NONE offaxishisto=NONE grhisto=NONE apstophisto=NONE
  mastaspectfile=nu40060001001_mast.fits attfile=nu40060001001_att.fits
  extended=yes psfflag=no grflag=no
```

5.8 Generation of RMF files (*'numkrmf'*)

The NuSTARDAS software module *'numkrmf'* generates an OGIP-style Response Matrix File (RMF) which is suitable for input into the spectral fitting program XSPEC.

The task requires in input the following files:

- Level 2 event file (FITS file)
- Source region file (ASCII file)
- CALDB RMF Grouping File (FITS file)

The file generated in output by the task is:

- RMF file (FITS file)

For NuSTAR, the CALDB stores two sets of RMF files, to be used for event files filtered or not filtered for the depth cut. Each set stores the RMF file appropriate for each detector pixel or group of detector pixels. The association between pixels and CALDB RMF files is specified in the CALDB RMF Grouping File provided in input through the parameter '*grprmffile'*.

'*numkrmf*' first reads the keyword 'DEPTHCUT' of the input event file (see Section 3.9) to select the appropriate '*grprmffile'* CALDB file. Next, for each CALDB RMF file, it computes the number of events in the input event file (*'infile'*) within the input spatial region file (parameter '*srcregionfile*').

The response of the detector is finally generated by '*numkrmf*' calculating a weighted mean of the CALDB RMF files. The mean is computed using as weights the corresponding number of events and making use of the multi-mission FTOOL '*addrmf*'. Optionally, by setting the input parameter '*cmprmf*' to 'yes', the output RMF file is compressed using the multi-mission FTOOL '*cmprmf*'.

This module is called by the *'nuproducts'* script.

Usage example:

1. Generates the RMF file appropriate for the input spatial region *'source.reg'*:

```
> numkrmf infile=nu40060001001A01_cl.evt srcregionfile=source.reg
  outfile=nu40060001001A01_sr.rmf
```

6 CALIBRATION FILES

6.1 Introduction

The NuSTARDAS software interfaces with the calibration information via the Calibration Database (CALDB) which consists of a collection of files, each dedicated to a specific aspect of calibration, organized in a specific directory structure. Software retrieves the CALDB files by querying an index file, which contains records of the calibration files and their validity.

The CALDB files for NuSTAR can be divided in three categories:

- Files used by the software to calibrate events, for example, to calculate the PI values, or to record standard screening criteria.
- Files used in the analysis of extracted products, for example, the response matrices.
- Files not used directly by the software that contain instrument characteristics and are included in the calibration database for archival purposes.

The following sections list the NuSTAR CALDB files that are directly used by the NuSTAR software tasks and in the analysis of extracted products.

The calibration files are named according to the following convention:

nu[instrument][datatype][date]v[ver].[ext]

where *[instrument]* indicates the focal plane module, *[datatype]* provides an identifier for the calibration data, *[date]* indicates the first date of validity of the file and *[ver]* is the version number for that file. E.g. *nuCmetgrid20100101v001.fits*.

6.2 Calibration files listing

The table in this section provides a quick reference for the calibration files required by the NuSTAR software tasks. The table contains five columns. The first lists the name of the software task; the second gives a brief description of the calibration files used by the task; the third indicates the Focal Plane Module ('A' for FPMA, 'B' for FPMB and 'C' for both) for which that calibration file is applicable; the fourth contains the *[datatype]* in the filename of the calibration file and/or the file extension (*[ext]*) if different from '.fits'; the last column lists the CALDB subdirectory containing the file.

Software Task	Calibration File Description	[Instrument]	[datatype]/[ext]	directory
numetrology	Metrology Grid	C	metgrid	/fpm/bcf/metrology/
	Alignment	C	align	/fpm/bcf/align/
nuattcorr	CHUs Quaternion Offset	C	chuoffset	/fpm/bcf/instrument/
nuflagbad	Ground Bad Pixel	A,B	badpix	/fpm/bcf/badpix/
nuhotpix	-	-	-	-
nucalcpha	Capacitors offset	A,B	offset	/fpm/bcf/cap_offset/
	Event Grade	C	grade	/fpm/bcf/grade/
	Energy Calibration Coefficients	A,B	phapar	/fpm/bcf/instrument/
nucalcpi	Gain coefficients	A,B	gain	/fpm/bcf/gain/
	Charge Loss Coefficients	A,B	clc	/fpm/bcf/clc/
	Fluorescence photons energy boundaries	C	clcfilter	/fpm/bcf/clc/
nuflagevt	Depth Cut Coefficients	A,B	depthcut	/fpm/bcf/instrument/
	Event Cut Coefficients	A,B	evtcut	/fpm/bcf/instrument/

nucoord	Pixel Position Coefficients	A,B	pixpos	/fpm/bcf/pixpos/
	Alignment	C	align	/fpm/bcf/align/
	Telescope definition	A,B	/.teldef	/fpm/bcf/teldef/
nucalcpos	Pixel Position Coefficients	A,B	pixpos	/fpm/bcf/pixpos/
	Alignment	C	align	/fpm/bcf/align/
nuskypos	Alignment	C	align	/fpm/bcf/align/
	Telescope definition	A,B	/.teldef	/fpm/bcf/teldef/
nucalcsaa	SAA Parameters	C	saapar	/fpm/bcf/instrument/
nufilter	makefilter parameters	C	mkconf	/fpm/bcf/instrument/
	prefilter parameters	C	preconf	/fpm/bcf/instrument/
	Telescope definition	A,B	/.teldef	/fpm/bcf/teldef/
nuscreen	Housekeeping range values Modes n = 1 to 6	A,B	hkrange0n	/fpm/bcf/instrument/
	GRADE and STATUS range values	A,B	evtrange	/fpm/bcf/instrument/
nulivetime	-	-	-	-
nuexpomap	Pixel Position Coefficients	A,B	pixpos	/fpm/bcf/pixpos/
	Alignment	C	align	/fpm/bcf/align/
	Telescope definition	A,B	/.teldef	/fpm/bcf/teldef/
	DET1 Instrument Probability Map	A,B	instrmap	/fpm/bcf/instrmap/
	Vignetting	A,B	vign	/fpm/bcf/vign/
nuskytodet	Alignment	C	align	/fpm/bcf/align/
	Telescope definition	A,B	/.teldef	/fpm/bcf/teldef/
nuproducts	Pixel Position Coefficients	A,B	pixpos	/fpm/bcf/pixpos/
	Alignment	C	align	/fpm/bcf/align/
	Telescope definition	A,B	/.teldef	/fpm/bcf/teldef/
	DET1 Instrument Probability Map	A,B	instrprobmap	/fpm/bcf/instrmap/
	Ancillary Response	A,B	/.arf	/fpm/bcf/arf/
	Raytrace 2D PSF	A,B	2dpsf	/fpm/bcf/psf/
	Vignetting	A,B	vign	/fpm/bcf/vign/
	Aperture Stop ARF Correction	A,B	apstop	/fpm/bcf/aperture_stop/
	Ghost Rays ARF Correction	A,B	gr	/fpm/bcf/ghost_rays/
	Detector Absorption Coefficients	A,B	detabs	/fpm/bcf/detabs/
	RMF files grouping	A,B	grprmf	/fpm/bcf/rmf/
nulccorr	Pixel Position Coefficients	A,B	pixpos	/fpm/bcf/pixpos/
	Alignment	C	align	/fpm/bcf/align/
	Telescope definition	A,B	/.teldef	/fpm/bcf/teldef/
	DET1 Instrument Probability Map	A,B	instrprobmap	/fpm/bcf/instrmap/
	Raytrace 2D PSF	A,B	2dpsf	/fpm/bcf/psf/
	Vignetting	A,B	vign	/fpm/bcf/vign/
nubackscale	Pixel Position Coefficients	A,B	pixpos	/fpm/bcf/pixpos/
	Alignment	C	align	/fpm/bcf/align/
	Telescope definition	A,B	/.teldef	/fpm/bcf/teldef/
	DET1 Instrument Probability Map	A,B	instrprobmap	/fpm/bcf/instrmap/
numkarf	Pixel Position Coefficients	A,B	pixpos	/fpm/bcf/pixpos/
	Alignment	C	align	/fpm/bcf/align/
	Telescope definition	A,B	/.teldef	/fpm/bcf/teldef/
	DET1 Instrument Probability Map	A,B	instrprobmap	/fpm/bcf/instrmap/

	Ancillary Response	A,B	/.arf	/fpm/bcf/arf/
	Raytrace 2D PSF	A,B	2dpsf	/fpm/bcf/psf/
	Vignetting	A,B	vign	/fpm/bcf/vign/
	Aperture Stop ARF Correction	A,B	apstop	/fpm/bcf/aperture_sop/
	Ghost Rays ARF Correction	A,B	gr	/fpm/bcf/ghost_rays/
	Detector Absorption Coefficients	A,B	detabs	/fpm/bcf/detabs/
numkrmf	RMF files grouping	A,B	grprmf	/fpm/bcf/rmf/

Table 6-1: Calibration Files

7 APPENDIX A: FITS FILE STRUCTURE

7.1 Level 1 File Format

The file structure of the telemetry formatted in FITS format is:

HDU	Type	EXTNAME	Dim(col)	Description
0	PRIMARY	-	0	Primary Header
1	BINTABLE	EVENTS	85(20)	Events Extension
2	BINTABLE	GTI	16(2)	GTI Extension

Table 7-1: Level 1 FITS File structure

The columns in the EVENTS extension are:

TTYPE	TFORM	TUNIT	TLMIN	TLMAX	TZERO	Description
TIME	1D	s	-	-	-	Event Time (seconds since Jan 1st 2010 00:00:00 UTC)
PRIOR	1D	s	-	-	-	Elapsed Livetime Since Prior Event - seconds.
NUMRISE	1J	-	-	-	-	Numerator of Time of Rise Estimator (17 bits, signed)
DENRISE	1J	-	-	-	-	Denominator of Time of Rise Estimator (14 bits, signed)
SUBFRM	1J	-	-	-	-	Time rel. to 1pps frame-sync: units: 16 1474560
PREPHAS	9I	-	-	-	-	Pre-trigger pulse-height values for central pixel plus 8 surrounding
POSTPHAS	9I	-	-	-	-	Post-trigger pulse-height values for central pixel plus 8 surrounding
RESET	1D	s	-	-	-	Event Time Relative to Most Recent Charge Pump Reset - seconds
TRIGGERS	9X	-	-	-	-	Hardware Triggers - same order as PRE and POST
DET_ID	1B	-	-	-	-	Detector ID (0,1,2,3)
S_CAP	1B	-	-	-	-	Starting Cap # (0..15)
HWTRIG	1B	-	-	-	-	Number of hardware triggers
RAWX	1B	-	-	-	-	X-position of central pixel in raw coordinates (column#: 0..31)
RAWY	1B	-	-	-	-	Y-position of central pixel in raw coordinates (row#: 0..31)
MODE	1B	-	-	-	-	1=CP mode, 0=Normal mode
STIM	1B	-	-	-	-	Stim event flag
UP	1B	-	-	-	-	uP (offset) event flag
SHIELD	1B	-	-	-	-	Shield hit flag
SHLD_T	1B	-	-	-	-	Shield timing (4 bits)
SHLD_HI	1B	-	-	-	-	High shield threshold flag

Table 7-2: Level 1 FITS File Events Table Columns

7.2 Level 1a File Format

The calibrated events FITS File structure is:

HDU	Type	EXTNAME	Dim(col)	Description
0	PRIMARY	-	0	Primary Header
1	BINTABLE	EVENTS	286(39)	Events Extension
2	BINTABLE	GTI	16(2)	GTI Extension
3	BINTABLE	BADPIX	20(5)	Bad pixels Extension for DET0
4	BINTABLE	BADPIX	20(5)	Bad pixels Extension for DET1
5	BINTABLE	BADPIX	20(5)	Bad pixels Extension for DET2
6	BINTABLE	BADPIX	20(5)	Bad pixels Extension for DET3

Table 7-3: Level 1a FITS File structure

The columns in the EVENTS extension are (the columns in the brackets may not be present, depending on the processing options):

TTYPE	TFORM	TUNIT	TLMIN	TLMAX	TZERO	Description
TIME	1D	s	-	-	-	Event Time (seconds since Jan 1st 2010 00:00:00 UTC)
PRIOR	1D	s	-	-	-	Elapsed Livetime Since Prior Event - seconds.
NUMRISE	1J	-	-	-	-	Numerator of Time of Rise Estimator (17 bits, signed)
DENRISE	1J	-	-	-	-	Denominator of Time of Rise Estimator (14 bits, signed)
SUBFRM	1J	-	-	-	-	Time rel. to 1pps frame-sync: units: 16 1474560
PREPHAS	9I	-	-	-	-	Pre-trigger pulse-height values for central pixel plus 8 surrounding
POSTPHAS	9I	-	-	-	-	Post-trigger pulse-height values for central pixel plus 8 surrounding
RESET	1D	s	-	-	-	Event Time Relative to Most Recent Charge Pump Reset - seconds
TRIGGERS	9X	-	-	-	-	Hardware Triggers - same order as PRE and POST
DET_ID	1B	-	-	-	-	Detector ID (0,1,2,3)
S_CAP	1B	-	-	-	-	Starting Cap # (0..15)
HWTRIG	1B	-	-	-	-	Number of hardware triggers
RAWX	1B	-	-	-	-	X-position of central pixel in raw coordinates (column#: 0..31)
RAWY	1B	-	-	-	-	Y-position of central pixel in raw coordinates (row#: 0..31)
MODE	1B	-	-	-	-	1=CP mode, 0=Normal mode
STIM	1B	-	-	-	-	Stim event flag
UP	1B	-	-	-	-	uP (offset) event flag
SHIELD	1B	-	-	-	-	Shield hit flag
SHLD_T	1B	-	-	-	-	Shield timing (4 bits)

SHLD_HI	1B	-	-	-	-	High shield threshold flag
STATUS	16X	-	-	-	-	Event Quality Flag
BADPOS	8X	-	-	-	-	Position of neighbor bad pixels
HOTPOS	8X	-	-	-	-	Position of neighbor hot/flickering pixels
(RAWPHAS)	9I	-	-	-	-	Pixel Pulse-height raw values
(OFFPHAS)	9E	-	-	-	-	Pixel Pulse-height after offset correction
(TRPHAS)	9E	-	-	-	-	Pixel Pulse-height after time of rise correction
(PHAS)	9E	-	-	-	-	Pulse-height after common mode correction
GRADE	I	-	0	32	-	Event Grade
SWTRIG	9B	-	-	-	-	Event software threshold Flag
PIS_GAIN	9E	chan	-	-	-	Pixel Pulse Invariant before charge loss correction
SURRPI	1J	-	-	-	-	um of pulse invariants for pixels below threshold
PI_CLC	1E	-	-	-	-	Pixel Pulse Invariant after charge loss correction
PI	J	-	0	4095	-	Pulse Invariant
DET1X	1I	pixel	1	360	-	Event X position Focal Plane Bench Frame
DET1Y	1I	pixel	1	360	-	Event Y position Focal Plane Bench Frame
DET2X	1I	pixel	1	600	-	Event X position Optics Bench Frame
DET2Y	1I	pixel	1	600	-	Event Y position Optics Bench Frame
X	1I	-	1	1000	-	Event X position SKY
Y	1I	-	1	1000	-	Event Y position SKY

Table 7-4: Level 1a FITS File Events Table Columns

7.3 Level 2 File Format

The cleaned and calibrated events FITS File structure is:

HDU	Type	EXTNAME	Dim(col)	Description
0	PRIMARY	-	0	Primary Header
1	BINTABLE	EVENTS	294(41)	Events Extension
2	BINTABLE	GTI	16(2)	GTI Extension
3	BINTABLE	BADPIX	20(5)	Bad pixels Extension for DET0
4	BINTABLE	BADPIX	20(5)	Bad pixels Extension for DET1
5	BINTABLE	BADPIX	20(5)	Bad pixels Extension for DET2
6	BINTABLE	BADPIX	20(5)	Bad pixels Extension for DET3

Table 7-5: Level 2 FITS File structure

The columns in the EVENTS extension are (the columns in the brackets may not be present, depending on the processing options):

TTYPE	TFORM	TUNIT	TLMIN	TLMAX	TZERO	Description
TIME	1D	s	-	-	-	Event Time (seconds since Jan 2010 00:00:00 UTC)
(PRIOR)	1D	s	-	-	-	Elapsed Livetime Since Prior Event - seconds.
(NUMRISE)	1J	-	-	-	-	Numerator of Time of Rise Estimator (17 bits, signed)
(DENRISE)	1J	-	-	-	-	Denominator of Time of Rise Estimator (14 bits, signed)
(SUBFRM)	1J	-	-	-	-	Time rel. to 1pps frame-sync: units: 16 1474560
(PREPHAS)	9I	-	-	-	-	Pre-trigger pulse-height values for central pixel plus 8 surrounding
(POSTPHAS)	9I	-	-	-	-	Post-trigger pulse-height values for central pixel plus 8 surrounding
(RESET)	1D	s	-	-	-	Event Time Relative to Most Recent Charge Pump Reset - seconds
(TRIGGERS)	9X	-	-	-	-	Hardware Triggers - same order as PRE and POST
DET_ID	1B	-	-	-	-	Detector ID (0,1,2,3)
(S_CAP)	1B	-	-	-	-	Starting Cap # (0..15)
(HWTRIG)	1B	-	-	-	-	Number of hardware triggers
RAWX	1B	-	-	-	-	X-position of central pixel in raw coordinates (column#: 0..31)
RAWY	1B	-	-	-	-	Y-position of central pixel in raw coordinates (row#: 0..31)
(MODE)	1B	-	-	-	-	1=CP mode, 0=Normal mode
(STIM)	1B	-	-	-	-	Stim event flag
(UP)	1B	-	-	-	-	uP (offset) event flag
(SHIELD)	1B	-	-	-	-	Shield hit flag
(SHLD_T)	1B	-	-	-	-	Shield timing (4 bits)
(SHLD_HI)	1B	-	-	-	-	High shield threshold flag
(STATUS)	16X	-	-	-	-	Event Quality Flag
(BADPOS)	8X	-	-	-	-	Position of neighbor bad pixels
(HOTPOS)	8X	-	-	-	-	Position of neighbor hot/flickering pixels
(RAWPHAS)	9I	-	-	-	-	Pixel Pulse-height raw values
(OFFPHAS)	9E	-	-	-	-	Pixel Pulse-height after offset correction
(TRPHAS)	9E	-	-	-	-	Pixel Pulse-height after time of rise correction
(PHAS)	9E	-	-	-	-	Pulse-height after common mode correction
GRADE	I	-	0	32	-	Event Grade
(SWTRIG)	9B	-	-	-	-	Event software threshold Flag
(PIS_GAIN)	9E	chan	-	-	-	Pixel Pulse Invariant before charge loss correction
SURRPI	1J	-	-	-	-	um of pulse invariants for pixels

						below threshold
(PI_CLC)	1E	-	-	-	-	Pixel Pulse Invariant after charge loss correction
PI	J	-	0	4095	-	Pulse Invariant
DET1X	1I	pixel	1	360	-	Event X position Focal Plane Bench Frame
DET1Y	1I	pixel	1	360	-	Event Y position Focal Plane Bench Frame
DET2X	1I	pixel	1	600	-	Event X position Optics Bench Frame
DET2Y	1I	pixel	1	600	-	Event Y position Optics Bench Frame
X	1I	-	1	1000	-	Event X position SKY
Y	1I	-	1	1000	-	Event Y position SKY

Table 7-6: Level 2 FITS File Events Table Columns

7.4 GTI table FITS Format

All event files have a GTI extension. The format is:

TTYPE	TFORM	TUNIT	TLMIN	TLMAX	TZERO	Description
START	1D	s	-	-	-	GTI Start Time
STOP	1D	s	-	-	-	GTI Stop Time

Table 7-7: GTI Table columns

7.5 Bad Pixel table FITS Format

All calibrated event files have a Bad pixels extension for each Detector ID. The format is:

TTYPE	TFORM	TUNIT	TLMIN	TLMAX	TZERO	Description
RAWX	1B	pixel	0	31	-	X-position in raw detector coordinates
RAWY	1B	pixel	0	31	-	Y-position in raw detector coordinates
TIME	1D	s	-	-	-	Start Time of Bad Pixel Interval
TIME_STOP	1D	s	-	-	-	Start Time of Bad Pixel Interval
BADFLAG	16X	-	-	-	-	Bad Pixel flag

Table 7-8: Bad Pixels Table columns

7.6 Filter File Format

The filter file structure is:

HDU	Type	EXTNAME	Dim(col)	Description
0	PRIMARY	-	0	Primary Header
1	BINTABLE	FILTER	115(37)	Filter Extension

Table 7-9: Filter FITS File structure

The columns in the FILTER extension are:

TTYPE	TFORM	TUNIT	TLMIN	TLMAX	TZERO	Description
TIME	1D	s	-	-	-	Time at which a value changed
OCCULTED	1B	-	-	-	-	Occulted Flag
SAA	1B	-	-	-	-	In SAA Flag (using flags/data from FPMA and FPMB)
SAA_A	1B	-	-	-	-	Time in SAA (using FPMA HK data only)
SAA_B	1B	-	-	-	-	Time in SAA (using FPMB HK data only)
GEOCOR	1D	GV	-	-	-	Vertical cutoff rigidity
DAY	1B	-	-	-	-	In Daylight Flag
SLEW	1B	-	-	-	-	Slew Flag
ORBIT	1J	-	-	-	-	Orbit number
SOURCE	1B	-	-	-	-	1 = CHU4, 2 = S/C bus, 3 = hybrid twixt 1&2
RESIDUAL	1B	-	-	-	-	CHU 4 Residual
LIVETIME	1D	s	-	-	-	Electronic livetime for current second
SHLDLO	1J	ct/s	-	-	-	Low-gain shield singles rate
SHLDHI	1J	ct/s	-	-	-	High-gain shield singles rate
SW_SAA	1B	-	-	-	-	ground software SAA flag
SW_TENTACLE	1B	-	-	-	-	ground software SAA flag
CAL0STAT	B	-	-	-	-	FPMA CAlibration src flag: 0=OUT, 1=IN
CAL1STAT	B	-	-	-	-	FPMB CAlibration src flag: 0=OUT, 1=IN
X0_INT	1E	mm	-	-	-	Sum of X laser intensities values for PSD0
Y0_INT	1E	mm	-	-	-	Sum of Y laser intensities values for PSD0
X1_INT	1E	mm	-	-	-	Sum of X laser intensities values for PSD1
Y1_INT	1E	mm	-	-	-	Sum of Y laser intensities values for PSD1
METGRID_FLAG	1B	-	-	-	-	MET Grid flag (=1 out of grid, =0 in grid)
ANG_DIST	1E	deg	-	-	-	angular distance of pointing from nominal
RA	1E	deg	-	-	-	pointing axis right ascension

DEC	1E	deg	-	-	-	pointing axis declination
ROLL	1E	deg	-	-	-	pointing axis roll
ELV	1E	deg	-	-	-	angle between pointing and earth limb
BR_EARTH	1E	deg	-	-	-	angle between pointing and bright earth
COR_SAX	1E	GeV/c	-	-	-	magnetic cut off rigidity
FOV_FLAG	1I	-	-	-	-	0=sky; 1=dark earth; 2=bright earth
MCILWAIN_L	1E	-	-	-	-	McIlwain L parameter (SAX)
MOON_ANGLE	1E	deg	-	-	-	angle between pointing and moon vector
RAM_ANGLE	1E	deg	-	-	-	angle between pointing and velocity vector
SAA_PREFILTER	1I	-	-	-	-	1=in SAA; 0=not
SUNSHINE	1I	-	-	-	-	1=in sunshine; 0=not
SUN_ANGLE	1E	deg	-	-	-	angle between pointing and sun vector

Table 7-10: Filter Table Columns

7.7 Optical Axis File Format

The file structure is:

HDU	Type	EXTNAME	Dim(col)	Description
0	PRIMARY	-	0	Primary Header
1	BINTABLE	OPTICAL_AXIS	56(7)	Optical Axis Extension

Table 7-11: Optical Axis FITS File structure

The columns in the OPTICAL_AXIS extension are:

TTYPE	TFORM	TUNIT	TLMIN	TLMAX	TZERO	Description
TIME	1D	s	-	-	-	Event Time
X_OA	1D	pixel	-	-	-	Optical Axis X position (SKY Frame)
Y_OA	1D	pixel	-	-	-	Optical Axis Y position (SKY Frame)
DET2X_APSTOP	1D	pixel	-	-	-	Aperture Stop Center DET2X position (OB Frame)
DET2Y_APSTOP	1D	pixel	-	-	-	Aperture Stop Center DET2Y position (OB Frame)
X_APSTOP	1D	pixel	-	-	-	Aperture Stop Center X position (SKY Frame)
Y_APSTOP	1D	pixel	-	-	-	Aperture Stop Center Y position (SKY Frame)

Table 7-12: Optical Axis Table Columns

7.8 DET1 Reference Pixel File Format

The file structure is:

HDU	Type	EXTNAME	Dim(col)	Description
0	PRIMARY	-	0	Primary Header
1	BINTABLE	DET1_REFPOINT	24(3)	DET1 Reference Pixel Extension

Table 7-13: DET1 Reference Pixel FITS File structure

The columns in the DET1_REFPOINT extension are:

TTYPE	TFORM	TUNIT	TLMIN	TLMAX	TZERO	Description
TIME	1D	s	-	-	-	Event Time
X_DET1	1D	pixel	-	-	-	Detector Reference Point X position (SKY Frame)
Y_DET1	1D	pixel	-	-	-	Detector Reference Point Y position (SKY Frame)

Table 7-14: DET1 Reference Pixel Table Columns

7.9 Mast aspect solution File Format

The file structure is:

HDU	Type	EXTNAME	Dim(col)	Description
0	PRIMARY	-	0	Primary Header
1	BINTABLE	MAST_ASPECT	64(3)	Mast aspect solution Extension

Table 7-15: Mast aspect solution FITS File structure

The columns in the MAST_ASPECT extension are:

TTYPE	TFORM	TUNIT	TLMIN	TLMAX	TZERO	Description
TIME	1D	s	-	-	-	Time of the mast aspect solution
T_FBOB	3D	mm	-	-	-	Translation from Focal Plane to Optical Plane
Q_FBOB	4D	-	-	-	-	Quaternion from Focal Plane to Optical Plane

Table 7-16: Mast aspect solution Table Columns

7.10 Position Sensing Detector File Format

The file structure is:

HDU	Type	EXTNAME	Dim(col)	Description
0	PRIMARY	-	0	Primary Header
1	BINTABLE	PSDPOS	40(9)	Position Sensing Detector Extension

Table 7-17: Position Sensing Detector FITS File structure

The columns in the PSDPOS extension are:

TTYPE	TFORM	TUNIT	TLMIN	TLMAX	TZERO	Description
TIME	1D	s	-	-	-	Time of laser position measurement
X_PSD0	1E	mm	-	-	-	X-position of laser spot on PSD0
Y_PSD0	1E	mm	-	-	-	Y-position of laser spot on PSD0
X_PSD1	1E	mm	-	-	-	X-position of laser spot on PSD1
Y_PSD1	1E	mm	-	-	-	Y-position of laser spot on PSD1
X0_INT	1E	mm	-	-	-	Sum of X laser intensities values for PSD0
Y0_INT	1E	mm	-	-	-	Sum of Y laser intensities values for PSD0
X1_INT	1E	mm	-	-	-	Sum of X laser intensities values for PSD1
Y1_INT	1E	mm	-	-	-	Sum of Y laser intensities values for PSD1
METGRID_FLAG	1B	-	-	-	-	MET Grid flag (=1 out of grid, =0 in grid)

Table 7-18: Position Sensing Detector Table Columns